

Ceiling Insulation Report: Effectiveness of Lay-In Ceiling Insulation

Effectiveness of Lay-In Insulation (product 5.2.6)

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PREFACE

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

This document is one of 33 technical attachments to the final report of a larger research effort called *Integrated Energy Systems: Productivity and Building Science Program* (Program) as part of the PIER Program funded by the California Energy Commission (Commission) and managed by the New Buildings Institute.

As the name suggests, it is not individual building components, equipment, or materials that optimize energy efficiency. Instead, energy efficiency is improved through the integrated design, construction, and operation of building systems. The *Integrated Energy Systems: Productivity and Building Science Program* research addressed six areas:

- Productivity and Interior Environments
- Integrated Design of Large Commercial HVAC Systems
- Integrated Design of Small Commercial HVAC Systems
- Integrated Design of Commercial Building Ceiling Systems
- Integrated Design of Residential Ducting & Air Flow Systems
- Outdoor Lighting Baseline Assessment

The Program's final report (Commission publication #P500-03-082) and its attachments are intended to provide a complete record of the objectives, methods, findings and accomplishments of the *Integrated Energy Systems: Productivity and Building Science Program*. The final report and attachments are highly applicable to architects, designers, contractors, building owners and operators, manufacturers, researchers, and the energy efficiency community.

This attachment, "Ceiling Insulation Report" (Attachment A-14), provides supplemental information to the program's final report within the **Integrated Design of Commercial Building Ceiling Systems** research area. It includes the following report:

- **Effectiveness of Lay-In Insulation.** In this study, researchers surveyed commercial buildings to identify how many have lay-in insulation and what fraction of the original lay-in insulation remains in place; researched application and cost issues of lay-in insulation versus alternative insulation methods; and calculated the energy and energy-cost impacts of these approaches.

The Buildings Program Area within the Public Interest Energy Research (PIER) Program produced these documents as part of a multi-project programmatic contract (#400-99-413). The Buildings Program includes new and existing buildings in both the residential and the non-residential sectors. The program seeks to decrease building energy use through research that will develop or improve energy efficient technologies, strategies, tools, and building performance evaluation methods.

For other reports produced within this contract or to obtain more information on the PIER Program, please visit www.energy.ca.gov/pier/buildings or contact the Commission's Publications Unit at 916-

654-5200. All reports, guidelines and attachments are also publicly available at www.newbuildings.org/pier.

ABSTRACT

The “Ceiling Insulation Report” was produced as a part of the Integrated Design of Commercial Building Ceiling Systems project. This was one of six research projects within the *Integrated Energy Systems: Productivity and Building Science* Program, funded by the California Energy Commission’s Public Interest Energy Research (PIER) Program.

When this project began, California energy codes allowed the use of lay-in insulation on top of dropped (T-bar) ceilings. This insulation method is fairly common due to its low installation cost but anecdotal reports indicate that insulation integrity is not maintained over time. In this study, researchers surveyed commercial buildings to identify how many have lay-in insulation and what fraction of the lay-in insulation remains in place; researched application and cost issues of lay-in insulation versus alternative insulation methods; and calculated the energy and energy-cost impacts of these approaches.

The energy analysis found that buildings with lay-in insulation over suspended ceilings in general had higher energy costs than other configurations. The incremental cost of insulating the roof deck instead of using lay-in insulation was very small. For plenum heights under 12 ft, insulating the roof and walls saved more life-cycle energy costs than the insulation’s incremental cost. This analysis resulted in a recommendation that the California building efficiency standards (Title 24) prohibit use of lay-in insulation over suspended ceilings for thermal insulation except for small spaces under plenums that are taller than 12 ft. This recommendation, if adopted, would affect Title 24’s Section 118: “Mandatory Requirements for Insulation and Cool Roofs.”

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Keywords: Title 24, insulation, lay-in insulation, suspended ceiling, dropped ceiling, T-bar, commercial building ceiling, roof deck insulation

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EXECUTIVE SUMMARY

Insulation position is as important as the quantity of insulation used to reduce HVAC loads in commercial buildings. This study compared the energy consumption and costs in commercial buildings for a number of insulation configurations: lay-in insulation above suspended acoustic ceilings, insulated drywall ceilings, and insulated roof decks.

Almost anyone who has peeked above suspended ceilings to maintain equipment or for energy audits can attest that lay-in insulation has been moved aside or is otherwise missing for some fraction of the ceiling area. However, we are unaware of any studies that have systematically quantified the fraction of ceiling area where insulation is missing.

This research project used phone surveys, field surveys, and analysis of various wall construction types to determine the prevalence and cost effectiveness of lay-in insulation and the alternative approaches.

The research team conducted 200 phone surveys of recently remodeled or constructed facilities. Of these buildings, skylights were present in 26% overall and in 37% of buildings with dropped ceilings while lay-in insulation was present in only 5% of the buildings.

During field surveys researchers found displaced or missing insulation in the majority of dropped ceilings. Site visits resulted in 39 observations of lay-in insulation coverage in 13 buildings. Missing insulation ranged between 10% and 90%, with most observations falling being between 10% and 40% of ceiling area with out insulation.

The energy analysis indicates that infiltration losses across the ceiling effectively by pass much of the insulating value of lay-in insulation. Thus the energy analysis is sensitive to the effective leakage area of the ceiling and the pressure gradient across the ceiling plane. To place high and low bounds on the results, the energy analysis was conducted with a low estimate of effective leakage area from the ASHRAE¹ Handbook of Fundamentals and a higher estimate based upon recent research by the Florida Solar Energy Center (FSEC).

Some of the key findings of the resulting energy analysis are:

- Buildings with lay-in insulation over suspended ceilings in general had 5-10% higher energy costs than other configurations unless plenum heights were very tall.
- Based on our analysis of results with FSEC infiltration rates, Insulated drywall ceilings are cost-effective only for frame construction in extreme

¹ American Society of Heating Refrigerating and Airconditioning Engineers

climate zones. The drywall ceilings were not cost effective for both the mass wall conditions studied, when compared to insulated roof decks.

- For mild climates (CTZ 3, 6): roof insulation is cost-effective when the plenum heights in mass buildings and frame wall buildings are less than 9 feet tall.
- For warmer climates (CTZ 10, 12, 14): roof insulation is cost-effective for all wall types for plenum heights up to 12 feet tall.
- The incremental cost of insulating the roof deck instead of lay-in insulation was very small. Higher initial cost is required if the plenum walls also need insulation. For plenum heights less than 12 feet, insulating the roof and walls saved more life-cycle energy costs than the incremental cost of the insulation.
- With roof insulation demonstrated as cost-effective compared to lay-in insulation, the research and analysis resulted in a recommendation that the draft 2005 California building efficiency standards (Title 24) prohibit use of lay-in insulation over suspended ceilings for thermal insulation except for small spaces under plenums that are taller than 12 feet. This recommendation, if adopted, would be contained in standards Section 118 - "Mandatory Requirements for Insulation and Cool Roofs"

INTRODUCTION

The research in this report has been designed to support the Integrated Design of Commercial Building Ceiling Systems research element. This research element consists of three related components:

1. Effectiveness of lay-in insulation
2. Comprehensive skylight testing
3. Development of an integrated ceiling system protocol for quality lighting (including daylight) and energy savings.

For more information on the two other components of the project, please contact the California Energy Commission PIER (Public Interest Energy Research) program.

Currently, insulating either the ceiling or the roof deck is considered equivalent by the California Building Efficiency Standards (Title 24, Part 6). This research summarizes research conducted to evaluate if laying insulation on top of an acoustic tile ceiling (lay-in insulation) is indeed equivalent to insulating the roof deck of commercial buildings. Lay-in insulation is also termed as “Backloaded Insulation” which can be defined as the thermal/acoustical insulation placed above the ceiling suspension system, laid across the horizontal grid members above the acoustical panels or tile².

The hypothesis of this research is that lay-in insulation is less effective than insulating the roof deck for two reasons:

1. Over time, insulation placed on the ceiling is moved during equipment maintenance in the plenum and during remodel. Thus the ceiling is not completely covered with insulation.
2. An acoustic tile ceiling is made up of many squares or rectangles held up by a grid. This segmented ceiling allows substantial amounts of air to pass around each tile. This exfiltration across the ceiling results in the insulation being thermally by-passed.

However, insulating the ceiling plane reduces the volume of conditioned space and the exterior wall area. Thus heat losses through the walls would be diminished for buildings with insulated ceilings. As a result, the research team collected data and analyzed thermal flows to answer the following key questions:

1. Does placing insulation at the roof deck save energy when compared to lay-in insulation?

² Armstrong ceilings - Terms and definitions. <http://www.armstrong.com/resceilingsna/article5068.asp>

2. If insulated roofs save energy, will the energy savings of roof insulation pay for the incremental cost of insulating roofs? Are insulated roofs a cost-effective alternative to lay-in insulation?

This report describes the analysis used to compare the energy impacts and cost-effectiveness of various methods of insulating the roofs and ceilings of commercial buildings. More specifically the energy performance of lay-in insulation on T-bar ceilings is compared to insulated drywall ceilings or insulating the roof deck of commercial buildings.

DATA COLLECTION

The information needed to perform the analysis of the effectiveness of lay-in insulation came from an earlier phase of this project as well as from research carried out on other projects. As will be described through this report, since energy impacts of lay-in insulation is dependent upon other components of the building envelope and mechanical systems, much of this work was performed in conjunction with parallel research on the value of sealing ducts in small nonresidential buildings.

Phone Interviews

To better understand the prevalence of the use of lay-in insulation, 200 managers of buildings recently constructed or remodeled, were contacted and interviewed about the presence of lay-in insulation in their buildings. A prior report on this project goes into the details of the phone interviews.³

The following conclusions were drawn from these interviews.

- Over half of the buildings in the sample were reported to have dropped ceilings (57%).
- Only 5% of the buildings with suspended acoustic ceilings were thought by the building managers to have lay-in insulation.
- 26% of the buildings in our interview sample had skylights. This is a substantially higher fraction of buildings with skylights than has been reported in the past.
- 37% of the buildings with suspended acoustic tile ceilings had skylights. This is a strong indicator of the potential benefit and impact of our research into an integrated ceiling system⁴

Site Surveys

The phone interviews identified buildings with lay-in insulation. Additional buildings were identified from other site surveys funded by another PIER project or by the California utilities as part of their efficiency programs. Managers of the buildings that were reported to have lay-in insulation were asked to allow a

³ *Lay-In Insulation Telephone Survey Procedure* See References for full citation

⁴ For barriers to using skylighting with suspended ceilings, see the Integrated Ceiling Research report. See references for full citation.

survey team to observe and record the fraction of ceiling area that was actually covered with lay-in insulation.

Survey Methodology

The onsite survey methodology involved selecting the building samples, creating an onsite survey form and a survey protocol for the surveyors to make onsite observations and measurements. These steps are described in detail below.

Sample Selection

Contrary to our initial hypothesis that lay-in insulation was a widespread practice, the results of the phone interviews were that lay-in insulation was being used at 5% or 10 of the 200 sites that responded to phone interviews. Only 8 of these sites agreed to give us access to their building. As a result, all of the sites responding affirmatively to the presence of lay-in insulation and giving the survey team access were included in the site surveys. Additional sites were identified from energy surveys being administered through the utility efficiency programs, prior research conducted by Lawrence Berkeley National Laboratories and the PIER research on small HVAC systems⁵.

The following summary lists the characteristics of the sample of buildings surveyed:

- Site surveys were performed on 13 non-residential buildings with surveyors taking a total of 36 observations above the acoustic ceiling tiles.
- Primary occupancy of buildings: 12 offices and one retail store.
- Secondary occupancy: one office also had 10% of floor area dedicated to classrooms, one office had 49% of the space dedicated to a recreation area and one office had 33% of it area dedicated to retail, the retail space had 19% dedicated to office space. Our sample was overwhelmingly office space.
- Building age: a range from 1 year to 50 years (see Figure 1). Of the 11 buildings with an estimate of building age, 7 of the buildings are 3 years old or less, the remaining buildings are over 20 years old.

⁵ Ernest Orlando Lawrence Berkeley National Laboratory, "Field Investigation of Duct System Performance in California Light Commercial Buildings", December 1997, Also see the reference section.

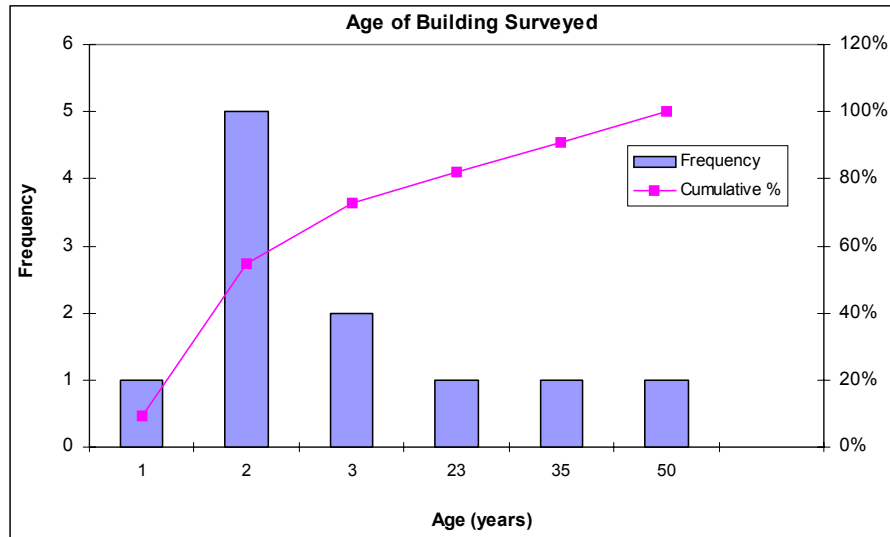


Figure 1: Age of buildings surveyed

- Of the 7 buildings that were reported to be remodeled most were remodeled in the last few years (see Figure 2). The managers of two buildings claimed that they hadn't been remodeled in over 15 years!

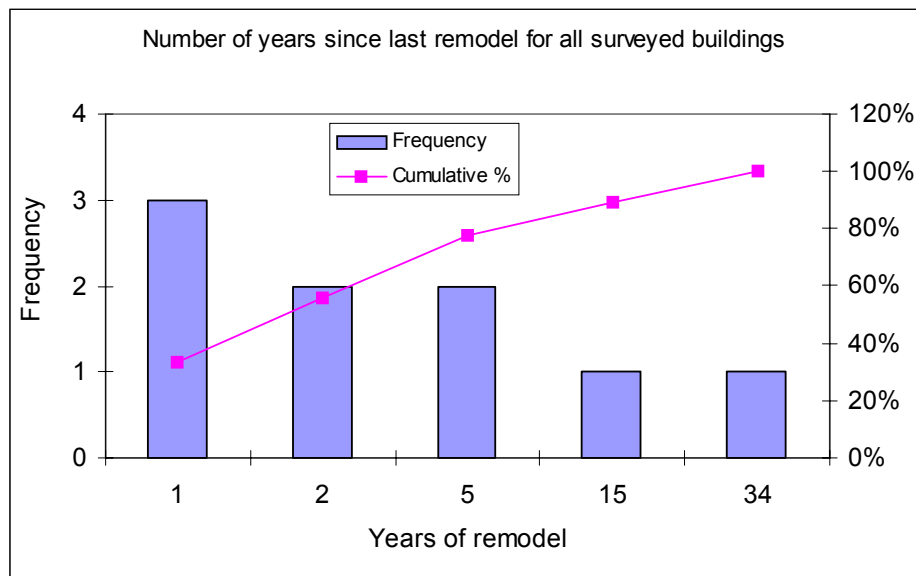


Figure 2: Number of years for surveyed buildings since last remodeled

- ♦ Floor area: The entire building floor area of buildings in the site survey sample ranged from 1,200 to 600,000 SF with most buildings being less than 50,000 SF. The floor areas of those sections of the buildings having lay-in insulation ranged from 1,000 to 15,000 SF (see Figure 3). Thus in general, the areas with lay-in insulation are relatively small.

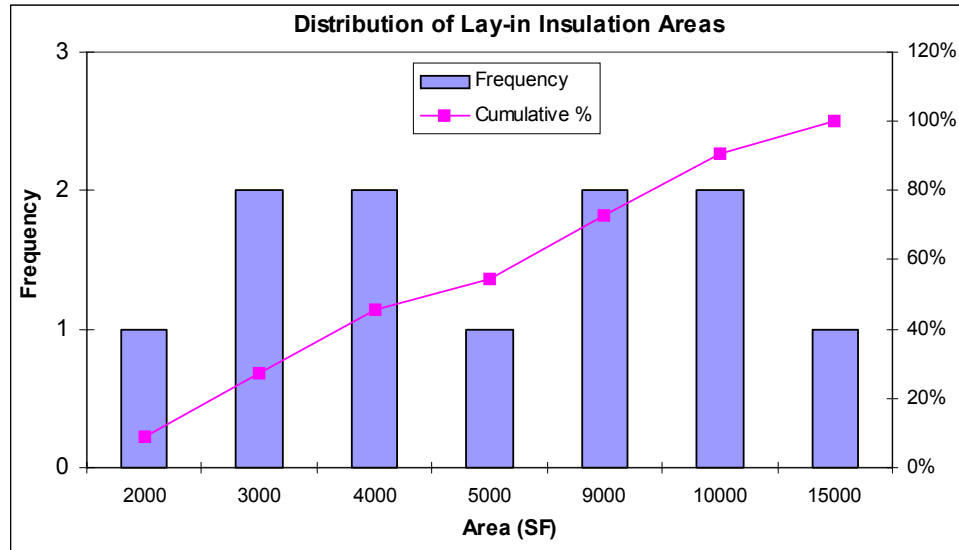


Figure 3: Area of lay-in insulation in surveyed buildings

- Number of stories: 10 single story buildings and 3 two story buildings
- Roof type: most were flat roofs, described as built-up
- Roof deck construction: 12 plywood decks and 1 metal roof deck
- Skylights: two buildings, or 15% of our sample, had skylights
- Plenum wall construction and insulation:
 - 4 of the buildings were cement block and it is believed that 2 of these had insulated block cores,
 - 6 buildings were of tilt up construction and two had insulated plenum walls
 - 3 buildings were wood frame construction and all had plenum side wall insulation
- Plenum heights: they varied from 1 feet to 20 feet (see Figure 4). The median plenum height was 6 feet while 80% of the plenum heights were less than 12 feet.

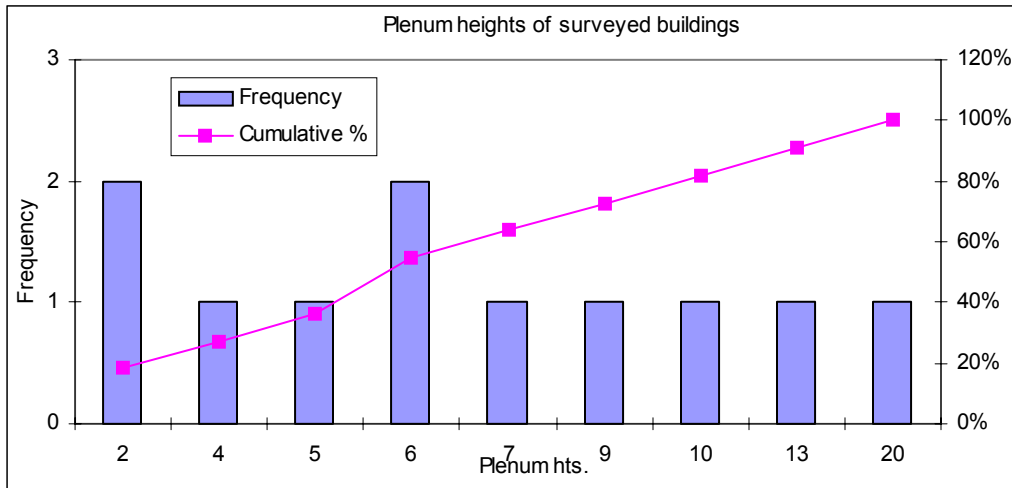


Figure 4: Average plenum heights of surveyed buildings

- Insulated lighting fixtures: only one building out of our sample had 2' by 4' fixtures that were covered with insulation. The rest were uncovered. In general, troffers are not IC (insulation contact) rated. Insulating most troffers is a fire hazard.

Survey form

A survey form was created for all onsite surveyors to fill up while at the site and the surveyors were trained on the study protocols. A detailed survey form used during onsite surveys is shown in Appendix D.

Onsite observations

Building overview

The surveyors interviewed the site contact about building construction, building age and recent remodels and if these remodels involved accessing top floor ceiling plenum, replacing ceiling tiles or roof. The building dimensions were measured. Observations on roof, wall construction type, slope if any, insulation type, location and area were made.

The surveyors then made a building sketch of the entire top floor footprint. This sketch included marking locations where measurements like height and square feet were made. Each roof, wall type and major wall orientation were also labeled.

Detailed plenum observations

This involved selecting 4—5 different locations within the top floor of each surveyed building. This helped cover a wide range of conditions within one building. With the help of a ladder the surveyors accessed the top floor plenum space above the drop ceiling by removing some ceiling tiles and made observations within the plenum space.



Figure 5: Surveyor accessing plenum space above the dropped ceiling

The surveyors sketched the ceiling plenum with approximate dimensions of ceiling area, location of ducts, recessed fixtures, walls extending through the ceiling, location of skylights if any, temperature measurements, direction of roof slope and area of missing insulation.

The surveyors recorded the average plenum height, plenum wall description and whether plenum is insulated. Temperature measurements in three locations within the plenum space were recorded: under roof deck, two thirds the plenum height and one-third the plenum height.

Insulation coverage was recorded according to the following conditions: Completely covered, partially covered, and totally uncovered. The surveyor collected detailed information on grid dimensions, tile count, sizes and conditions, recessed light fixture counts and conditions. From this detailed information, total insulation conditions and overall ceiling system conditions were calculated.



Figure 6: Plenum space indicating lay-in insulation on ceiling tiles. Also note missing insulation on recessed light can in photo on the right

Surveyors observed that some buildings had displaced insulation within the plenum space that was moved around during retrofits shown in Figure 7. Missing insulation can be broadly categorized as follows:

- Insulation pushed out of the way near access to mechanical or electrical equipment, or data cabling.
- Insulation not installed where there was little room beneath ducts or air handlers
- Insulation not installed for the remainder of a ceiling tile when HVAC diffusers, smaller light fixtures (2' x 2' troffers or recessed can lights) or other ceiling mounted equipment took up less than an entire tile.
- Rooms which had been remodeled where it appears the only a small fraction of the lay-in insulation was replaced.



Figure 7: Displaced lay-in insulation in the plenum space

Figure 8 illustrates an alternative to lay-in insulation - insulating plenum sidewalls and the underside of the roof deck. Rarely is the insulation missing from the underside of the roof deck nor from the plenum sidewalls. The reason for this is

that roof or wall insulation is generally not in the path of access to building services equipment.



Figure 8: Insulation under roof deck with insulated plenum walls

Photographs were taken of all the surveyed buildings along with their plenum space.

Site Survey Results

The on-site survey information was entered in spreadsheets and the data summarized. The primary output of this effort was to identify just how much of the ceiling area ends up being uninsulated over the long term. This data is plotted in Figure 9 for buildings of various ages.

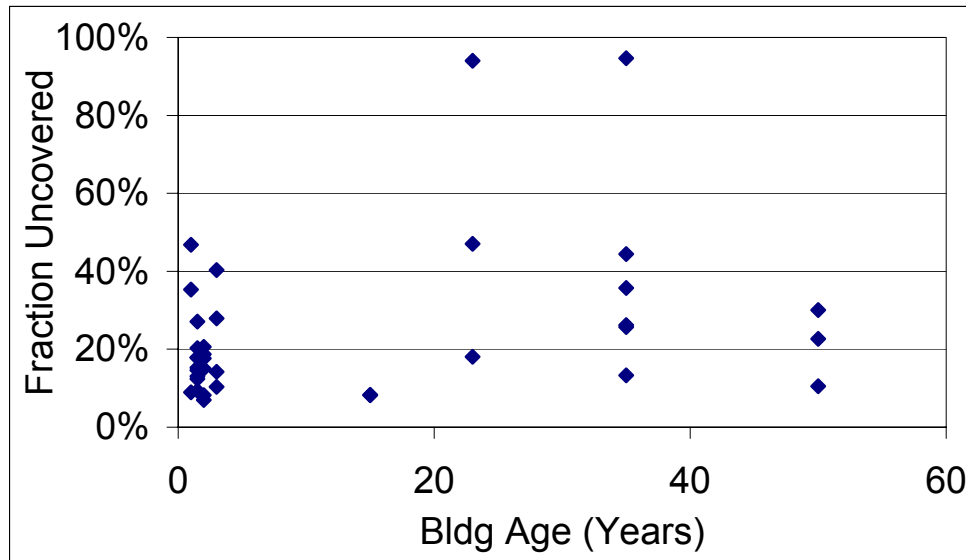


Figure 9: Fraction of ceiling uninsulated compared to building age

We have drawn the following conclusions from the data in Figure 9:

- If the two outlier observations (with over 90% of the ceiling uninsulated) are eliminated—there is essentially no correlation between building age and fraction of the ceiling that is uncovered. New buildings perform essentially the same as old buildings in this respect.
- Most of the data falls between 10% uncovered and 45% uncovered.
- When only 10% of the ceiling area is uncovered it is not because 10% of the tiles were covered but that all of the recessed troffers were uncovered. These troffers *should* be uncovered because they are not designed to be insulated and may overheat or catch fire if they are covered with insulation.

This information is the basis of much of the technical analysis conducted in the following section and reported in the rest of this document. Though there is a lack of a clear trend with respect to building age, the observation that much of the insulation is tossed aside near equipment access would indicate that improving initial insulation installation would not solve the problem of maintained insulation coverage.

California Title 24 Insulation Requirements

The insulation requirements for walls in the 2001 California Energy Efficiency Standards (Title 24, Part 6) can be calculated two different ways—R-factor or U-value—with dramatically different results. The first method is based upon the R-value of the insulation applied. This method is easy to calculate and easy to enforce. The second method recognizes that the thermal loads in a high-mass building are lower than those in a low-mass building due to thermal storage effects by the mass in the building. Heat loads on both the interior and exterior of

the building are absorbed by the building walls and released at night. As a result, medium and high-mass (masonry) buildings have substantially higher U-factor allowances than low-mass (frame wall) buildings. One can also use a U-factor method for roofs but they do not vary with respect to thermal mass and are very similar (if not more stringent) to the R-factor requirements.

From discussions with the Tilt-Up Concrete Association and Dave Kelley at Meadow-Burke Engineering, the thickness of single-story tilt-up walls in California ranges between 6-1/4 and 7-1/4 inches depending upon seismic zone. In seismic zone 3 (much of the Central Valley) the typical thickness is 6-1/4 inches and in seismic zone 4 (Bay Area and LA Basin) the typical thickness is 7-1/4 inches. Figure 10 shows a map of the seismic zones in California.⁶

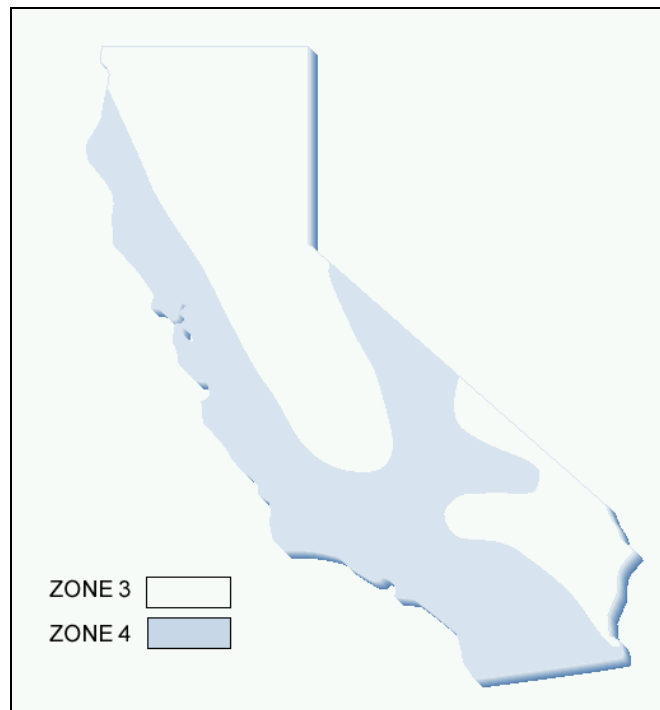


Figure 10: Statewide California Seismic Zone Map

Table 1 excerpts the wall and roof requirements for the climate zones 3, 6, 10, 12 and 14.⁷ The 7-1/4-inch thick tilt-up walls we have modeled in our analysis have a heat capacity, HC, of 16.7 and thus are considered high mass (an HC greater than 15 Btu/ft²·°F). The requirements for high mass walls are in bold in Table 1.

⁶ California Seismic Safety Commission. "The Homeowners Guide to Earthquake Safety," 1998 Edition. http://www.seismic.ca.gov/pub/CSSC_1997-01_HOG.pdf

⁷ Values are from Table 1-H – Prescriptive Envelope Criteria for Nonresidential Buildings, Section 143 Prescriptive Requirements for Building Envelopes, 2001 California Energy Efficiency Standards

Table 1: California energy efficiency requirements for opaque walls and roofs (as given in 2001 Building Energy Standards)

	Climate Zones				
Description	1,16	3—5	6—9	2, 10–13	14–15
Wall R-Value OR,	13	11	11	13	13
Wall U-factor					
Wood frame	0.084	0.092	0.092	0.084	0.084
Metal frame	0.182	0.189	0.189	0.182	0.182
Mass, $7 < HC < 15$	0.340	0.430	0.430	0.430	0.430
Mass, $15 < HC$	0.360	0.650	0.690	0.650	0.400
Roof R-Value	19	19	11	19	19
Roof U-factor	0.057	0.057	0.078	0.057	0.057

If the U-factor method is used, the U-factor requirement for 7-1/4" thick tilt up walls is equal to or greater than 0.650 [Btu/h·ft²·°F] for climate zones 2 through 13 for an overall R-value of only 1.54 [h·ft²·°F/Btu]. In section 141(c) 4.A of the CA Building Efficiency Standards, air film resistances are also allowed which in most cases is 0.17 [h·ft²·°F/Btu] outside and 0.68 [h·ft²·°F/Btu] inside so that the thermal resistance without air films of the medium mass wall need only be 0.69 [h·ft²·°F/Btu]. Given that a nominal 8" tilt-up slab (thickness of 7-1/4 inches) has an R-value of 0.80 to 0.48, the slab itself, or the slab in addition to an inch of stucco (R-value of 0.2) will provide the needed thermal resistance without adding insulation.⁸

Phone interviews were conducted with architects, insulation contractors and energy consultants to find out whether tilt up concrete walls were insulated in the conditioned space and in the plenum above insulated and uninsulated ceilings. The response was that if the wall is furred out to hide electrical wiring and plumbing, then the wall cavity was filled with insulation.

In the case of tilt up concrete walls, this brief survey found that when lay-in insulation was used, the plenum walls were not insulated. When the insulation is not placed at the ceiling but at the roof deck, the tilt-up walls on the sides of the plenum may or may not be insulated. This depended on the climate zone and occupancy. To reflect the diversity of construction practices, one could expect the following allowable methods of plenum construction (described in the next chapter):

⁸ p. 22.8 of the 1993 ASHRAE Handbook of Fundamentals thermal resistance values for 144 lb/ft³ concrete. The 1993 Handbook is referenced here as the 1993 Handbook is referenced in the Standard. Stucco values are from the DOE-2.1A Reference Manual.

- Mass construction with insulated roof deck
 - Insulated plenum side walls, or
 - Uninsulated plenum side walls
- Mass construction with ceiling insulation
 - Uninsulated plenum side walls
- Frame construction with insulated roof deck
 - Insulated plenum side walls
- Frame construction with ceiling insulation
 - Uninsulated plenum side walls

ENERGY ANALYSIS METHODOLOGY

Building Simulation Models

The following text describes the methodology used for DOE2.2 simulation runs for comparing the energy impacts of various methods of insulating the roofs and ceilings of commercial buildings. The model used was created by Architectural Energy Corporation to investigate the impacts of duct leakage on small commercial building energy consumption. Given that insulation position affects the energy impacts of duct leakage and vice versa, we combined our efforts in a single building simulation model.

Thus the estimates about the energy trade-offs between “lay-in” insulation laid on top of acoustic ceiling tiles versus insulation installed on top or directly below the roof deck, can be qualified by the amount of duct leakage in the plenum

The approach that the California 2001 Building Efficiency (Title 24) Standards used was a seasonal multiplier on HVAC system efficiency derived from ASHRAE Standard 152. Since the CEC staff has supported time-dependent valuation (TDV) for evaluation of cost-effectiveness and for comparison of trade-offs in the performance method (Alternative Compliance Method or ACM) in the 2005 Title 24 standards, our analysis uses TDV. The impact of duct tightening is expected to vary as a function of time and temperature, thus a single value approach will tend to underestimate the impacts under peak conditions. It is necessary to evaluate the impacts of duct tightening on an 8760 hourly basis to fully implement the TDV procedure⁹.

Options for including duct tightening in Title 24 nonresidential compliance were examined by Franconi (CEC, 1999). The work focused on the issues related to modeling duct leakage in DOE-2.1E in large and small commercial buildings, and identified several shortcomings in the program related to duct leakage modeling. Despite these shortcomings, Franconi recommends using DOE-2 as the duct compliance tool based on the key role the program already plays in the nonresidential compliance process. Since the work was published, capabilities to model return-side leakage, and the ability to specify the source of the makeup air (either outdoors or a buffer zone containing the duct system) have been added to the DOE-2.2 program. Many of the remaining limitations are more critical for larger building with VAV systems that fall outside of the proposed duct sealing standards. A summary of the limitations cited by Franconi, and comments reflecting more recent developments are shown in Table 2 below:

⁹ Pacific Gas & Electric Company. *Time Dependent Valuation (TDV) – Economics Methodology*. Code Change Proposal for 2005 Title 24 Building Energy Efficiency Standards Update, March 2002.

Table 2: Limitations of DOE-2 Models and Comments

Limitation	Comments
Savings not calculated for re-sizing fans after leakage sealing	Not an issue in small buildings, since fan flows are generally not adjusted.
Leakage makeup air comes from ambient	DOE-2.2 allows specification of a mixture of outdoor and return air as the source of the makeup air
Conduction and leakage losses not modeled for return systems	Return-side leakage losses modeled using DOE-2.2; conduction losses are not.
Duct heat loss coefficients are constant, ignoring variations in loss coefficients as a function of air flow, radiation, and duct/ambient delta T.	Limitation still exists
Fixed leakage rate assumption	Appropriate for constant volume systems
No explicit link between duct leakage and infiltration	Limitation still exists, but not an issue for balanced supply and return leakage or low leakage rates.

To estimate the cost effectiveness of roof versus ceiling insulation and ceiling infiltration, a series of simulation studies were undertaken in conjunction with the research team that was investigating the cost-effectiveness of duct tightening. First, a simple “box” prototype model was developed to test the capabilities and evaluate the response of the DOE-2.2 program to several duct efficiency and operating condition assumptions. The eQUEST program was used to develop the basic DOE-2.2 input file. Manual changes were made to the text input file to complete the analysis.

Table 3: DOE-2.2 Base Model Inputs

Model Parameter	Value
Shape	Rectangular, 50x40
Conditioned floor area	2000 SF
No Floors	1
Floor to ceiling	9 ft
Plenum ht	3 ft
Window/wall ratio	20%
Window type	CTZ 3,6 – Double low e clear (SHGC =0.42; COG U-value = 0.23), CTZ 10,12,14 – Double low e tint (SHGC = 0.37, COG U-value = 0.26)
Exterior wall construction	8 in. concrete tilt-up construction insulated
Exterior wall R-Value	CTZ 3,6 R-11 CTZ 10,12,14 – R-13
Infiltration rate	0.3 ACH in occupied zone, varies in attic
Roof construction	Built-up roof over plywood deck
Roof absorptivity and emissivity	Abs = 0.8; emiss = 0.9
Ceiling construction	Acoustic tile
Lighting power density	1.2 W/SF
Equipment power density	0.5 W/SF
Operating schedule	7 am - 6 pm M-F
No. People	11
Outdoor air	15 CFM/person
HVAC system	PSZ
Size	6 ton
CFM	2100 CFM
Sensible Heat Ratio @ ARI conditions	0.7
EER	8.5
Thermostat setpoints	Heating: 70/55; Cooling: 74/85
Fan power	0.375 W/CFM
Supply duct surface area	27% of floor area, per ACM
Duct leakage	36% total leakage; evenly split between supply and return (18% supply, 18% return) for leaky case, 10% total leakage for tight case
Duct insulation R-value	R-4.2, with an air film resistance of 0.7 added to account for external and internal air film resistance.
Return leak from outside air	0%
Return system type	ducted

Plenum Wall Model

To consider the impact of wall mass and plenum wall insulation, we modeled three different plenum side wall conditions: an insulated high mass wall, an uninsulated high mass wall and an insulated frame wall.

- The cement tilt-up walls in the DOE2.2 simulation are modeled as a full 8 inches thick, have an R-value of 0.88 and HC of 18.7.
- The frame walls are modeled as having an exterior finish of stucco, ½ inch plywood board with insulation installed between the framing members. The insulated walls of the ceiling plenum are not finished, but to maintain appropriate fire rating of the wall assembly foil faced batt insulation is assumed. R-value of wood frame wall (excluding the insulation) was calculated as 0.83 and HC as 3.18.

All of these walls are modeled as DOE-2 "layers" with thermal response factors so that the thermal mass is accurately characterized. For the models with plenum wall insulation, another layer was added to the wall properties to account for the thermal resistance of the insulation. The R-value of the insulation applied to the inside surfaces of plenum walls followed the requirements of the Title 24 building standards when the R-value method is used to show compliance (shown in Table 1 in the previous section). Thus R-11 insulation was added to the plenum side walls in climate zones 3 through 9 and R-13 insulation was added to the plenum side walls in the remainder of the climate zones.

The fiberglass batt insulation has a foil faced vapor barrier to comply with fire safety codes – Kraft paper faced batts do not meet the flame spread requirements. Foil faced batts were commonly used in the buildings we surveyed. Thus the insulation modeled is foil faced which has a low surface emittance and as a result this foil facing increases the interior film R-value increased from 0.68 (emittance = 90%) to 1.35 (emittance = 20%).¹⁰ The Surface Resistance for Air section of this report goes into more detail on the air film heat transfer coefficients used in the simulation models.

Roofs

Four types of roofing/ceiling combinations were analyzed.

1. The "under deck" insulated roof is a built-up roof over a plywood deck with foil faced R-11 or R-19 (depending on climate zone) fiberglass batts installed between metal joists under the roof deck. The ceiling model has an uninsulated T-bar ceiling with acoustic tiles.

¹⁰ Table 1 "Surface Conductances and Resistances for Air," 1993 ASHRAE Handbook of Fundamentals, p 22.1.

2. The “above deck” insulated roof has R-11 or R-19 polystyrene insulation sandwiched between the built-up roofing and the plywood deck. The ceiling in this model is an uninsulated T-bar ceiling with acoustic tiles.
3. The “drywall” insulated ceiling has built-up roofing over an uninsulated plywood deck. The ceiling is gypsum drywall with wooden joists. Foil faced R-11 or R-19 fiberglass batts are installed between the wood joists on top of the drywall ceiling.
4. The “lay-in” insulated ceiling has built-up roofing over an uninsulated plywood deck. The acoustic tile T-bar ceiling is insulated with R-11 or R-19 foil faced fiberglass batts. Insulation coverage is parametrically varied to cover between 90% to 50 % of the ceiling surface. These variations in insulation coverage are combined as described in the “Lay-in Insulation Coverage Probability Function” section.

R-Value Calculations

The R-values of each building components and the total R-value of the building system were calculated using the 1993 ASHRAE Fundamentals and the ASHRAE standards. This does not include the inside and outside surface resistance of air. The R values for roofs have been calculated on the basis of R-19 (CT3, CT10, CT12, CT14) and R-11 (CT6).

The R-value for roofs and walls were calculated using the R-values of individual layers of construction material and a sum of the individual layers (assuming a combination of layers in series or parallel heat flow path) was taken as the total R-value of that particular roof or wall type. Parallel heat flow is calculated by summing the U-factors at each insulation condition and fraction of the area represented.

$$U_{\text{eff}} = U_1F_1 + U_2F_2 + U_3F_3$$

Where,

U_1 = The U-factor of each wall or ceiling assembly (Btu/hr. °F.SF)

F_1 = Fraction of total wall or ceiling area of a given assembly

The U-factor of each assembly has a different series combination of layers and these layers are added as thermal resistances and inverted to find the U-factor

$$U_1 = 1 / R_{i1} + R_{i2} + R_{i3}$$

R_{i1} = Thermal resistance of component layer ‘1’ in wall or ceiling assembly “i” (°F.hr.SF/Btu).

The inside and outside surface resistance of air was then added to these R-values in the simulation model.

Table 4: R- value calculation of Roofs, Walls, and drywall ceiling

ROOFS					
For CTZ 3, 10, 12, 14 (R-19)			For CTZ 6 (R-11)		
Underdeck insulated roof					
built-up roof	0.33		built-up-roof	0.33	
plywood (.75 inch)	0.93		plywood (.75 inch)	0.93	
Corrected value of fiber	16.3		Corrected value of fiber	10	
Total	17.56		Total	11.26	
U factor	0.057		U factor	0.089	
Above deck insulated roof					
built-up roof	0.33		built-up roof	0.33	
plywood (.75 inch)	0.93		plywood (.75 inch)	0.93	
mineral fiber (6.5 inch)	19		mineral fiber (6.5 inch)	11	
Total	20.26		Total	12.26	
U factor	0.049		U factor	0.082	
Dry wall ceiling- R value					
Mineral fiber	19 wood joist	0.94	Mineral fiber	11 wood joist	0.94
Gypboard	0.45	0.45	Gypboard	0.45	0.45
R values	19.45	1.39	R values	11.45	1.39
Total	17.64		total	10.44	
U factor	0.057		U factor	0.096	

WALLS					
For CTZ 3, 6 (R-11)			For CTZ 10, 12, 14 (R-13)		
Plenum (mass wall)-insulated					
6"heavy wt concrete	1.23	1.93	6" light wt concrete	1.23	1.93
fiber glass batt	11 wood joist	0.94	fiber glass batt	13 wood joist	0.94
stucco	0.2		stucco	0.2	
R value	12.43	2.87	R value	14.43	2.87
Total	11.47		Total	13.27	
U factor	0.087		U factor	0.075	

Plenum (mass wall)-Uninsulated		
6" heavy wt concrete	1.23	
stucco	0.2	
Total	1.43	
U factor	0.699	

Plenum Wall (wood)-insulated					
1/2 in plywood			1/2 in plywood		
fiber glass batt	11 wood joist	4.38	fiber glass batt	13 wood joist	4.38
stucco			stucco		
R value	11.00	4.38	R value	13.00	4.38
Total	10.34		Total	12.14	
U factor	0.097		U factor	0.082	

Table 5 indicates the R-value calculation of suspended ceilings with 50%-90% insulation coverage. The overall R-values and U-values were calculated by assuming parallel heat flow path through the ceiling (insulation, ceiling tile and light fixture). The infiltration rates (refer to section "Total Ceiling U-factors") along with outside and inside air films (refer to section "Surface Resistance for Air") were then added to these R-values.

Table 5: R-value calculation for suspended tile ceilings

FOR INSULATION R-13							
%Insul.	R-value of insulation	R-value of ceiling tile	F1 (U-value of insulation+ceiling)	F2 (U-value of ceiling)	F3 (U-value-light fixture)	U-total	R-Total
0.9	19	1.25	0.044	0.000	0.033	0.078	12.857
0.8	19	1.25	0.040	0.080	0.033	0.153	6.543
0.7	19	1.25	0.035	0.160	0.033	0.228	4.388
0.6	19	1.25	0.030	0.240	0.033	0.303	3.301
0.5	19	1.25	0.025	0.320	0.033	0.378	2.645

FOR INSULATION R-11							
%Insul.	R-value of insulation	R-value of ceiling tile	F1 (U-value of insulation+ceiling)	F2 (U-value of ceiling)	F3 (U-value-light fixture)	U-total	R-Total
0.9	11	1.25	0.057	0.000	0.033	0.090	11.106
0.8	11	1.25	0.050	0.032	0.033	0.116	8.613
0.7	11	1.25	0.044	0.065	0.033	0.142	7.034
0.6	11	1.25	0.038	0.097	0.033	0.168	5.944
0.5	11	1.25	0.032	0.129	0.033	0.194	5.147

Heat Capacity Calculations

Heat Capacity for the roof systems and the wall systems is calculated using the specific heat, density and thickness of the building materials. The heat capacity, in units of Btu/ft²·°F is calculated from properties of building materials by the following equation:

$$HC = C_p \times \rho \times L$$

Where,

C_p = specific heat, Btu/lb_m·°F

ρ = density, lb_m/ft³

L = thickness of materials, ft

Table 6: Heat Capacities of Building Materials

Material	Specific Heat (Btu/lb _m ·°F)	Density (lb _m /sf)	Thickness (ft)	Heat Capacity (Btu/°F)
Tit-up slab, 8" thick heavy weight concrete	0.2	140	0.604	16.92
Roof deck, 1" plywood	0.29	34	0.06	0.62
R-19 Rigid insulation	0.2	6	0.29	0.35
Acoustic tiles	0.32	18	0.04	0.36
Drywall (gypsum board)	0.2	50	0.04	0.42
Stucco	0.2	166	0.08	2.77
½" plywood for frame wall	0.29	34	0.041	0.41

According to the 2001 Energy Efficiency Standards, the required U value of the wall is dependent on the heat capacity of the wall for various climate zones as described in section “California Title 24 Insulation Requirements”.

Surface Resistance for Air

The surface resistance for air for both the plenum wall and the roof is listed. This is not included in the calculation for R value of the various building component layers. The surface resistance of air changes with the surface orientation (wall or roof), emissivity of surface (reflective/non-reflective), and direction of heat flow (2001 ASHRAE fundamentals).

Table 7: Surface Resistance of Air for Roofs, Ceilings and Walls

Description	Surface orientation	Direction-heat flow	Surface	Emittance	R-value
Plenum wall	vertical	horizontal	reflective	0.2	1.35
Plenum wall	vertical	horizontal	non-reflective	0.9	0.68
Insulation under roof deck	horizontal	downward	reflective	0.2	2.7
Lay-in insulation	horizontal	downward	reflective	0.2	2.7
Ceiling(without insulation)	horizontal	downward	non-reflective	0.9	0.92
Insulation above roof deck	horizontal	downward	non-reflective	0.9	0.92

Ceiling Leakage

The intent of this project as to consider only the thermal transmittance aspects of lay-in insulation over T-bar ceilings. One of the questions that arose for the energy code evaluation was should a hard (drywall) ceiling be allowed as an alternative to insulating the roof deck? If infiltration or exfiltration across the ceiling barrier was not considered, then there essentially was no difference between the drywall ceiling and the acoustic tile ceiling other than the split of heat flows from luminaires (see Heat Loss from Luminaires below).

It became apparent that the assumption of no ceiling leakage would produce answers that were contrary to the results expected when ceiling leakage was included. Thus this study made use of the ceiling leakage results from previous studies. These studies were:

- An in-house study conducted by Armstrong World Industries in a test cell of four 2 ft by 2 ft acoustic ceiling tiles. A differential pressure of 0.5 inches of water column (125 Pa) was created across the ceiling plane and the flowrates measured. Also measured were the leakage of a 2 ft by 2 ft lensed fluorescent fixture and a recessed can. This study is unpublished.
- The ASHRAE Handbook of Fundamentals contains a table of effective leakage areas for a variety of building components at a reference pressure of

4 Pascals.¹¹ The values for a dropped ceiling are 10 times lower than those for a “general ceiling.” We are assuming that these figures are transposed and the value for the general ceiling is in fact the correct value for a dropped ceiling and vice versa. If this assumption is true, this result matches reasonably well the data collected by Armstrong World Industries.

- The Florida Solar Energy Center (FSEC), in a 1998 article in the ASHRAE Transactions measured ceiling leakages that are 10 times higher than either the ASHRAE or Armstrong values.¹² This FSEC study focused on field testing small commercial buildings with building cavities as part of air distribution system. Testing found that these building cavities are considered more leaky than standard ducts and plenums because they are not built to the same air tightness standard as ducts. Actual air leakage is a function not only of duct hole size but also pressure differential across the leak sites.

The leakage values of ceiling were presented in different formats: effective leakage area (reference pressure of 4 Pa), cfm at 50 Pascal and cfm at 25 Pascal differential pressure.

To maintain a consistent, reporting format this information is converted into an effective leakage area, A_{r1} (in²), at the reference pressure of 4 Pa (0.016 in WC) using the following formula¹³.

$$A_{r1} = \frac{Q_{r2}}{C_6 C_D \sqrt{\frac{2}{\rho}} (\Delta P_{r1})^{0.5-n} (\Delta P_{r2})^n}$$

where

- Q_{r2} = flowrate at pressure difference ΔP_{r2} , cfm
 C_6 = conversion unit factor = 5.39
 CD = coefficient of discharge = 1.0
 ρ = density of air, 0.075 lb_m/ft³
 ΔP_{r1} = reference pressure differential, 0.016 in WC
 ΔP_{r2} = pressure differential at alternate pressure, in WC
 n = pressure exponent, 0.65

Table 8 provides the infiltration rates that are quoted by different sources and places them into consistent units either the effective leakage area or the flowrate at the reference pressure of 4 Pascals. As will be discussed later, we will be

¹¹ p. 26.15, Table 1, Effective Air Leakage Areas (Low-Rise Residential Applications Only), 2001 ASHRAE Handbook of Fundamentals

¹² Cummings J B, Withers C. R. 1998. "Building cavities used as ducts: air leakage characteristics and impacts in light commercial buildings" ASHRAE Trans. 1998.

¹³ Accomplished by rewriting Equation 35 and solving for A_{r1} p. 26.13 2001 ASHRAE Fundamentals

evaluating the infiltration flows across the ceiling plane at even lower differential pressures than the 4 Pascal “reference pressure.”

Table 8: Effective Leakage Area of Ceiling Components from Various Sources

Source	Quoted values		CFM/sf @4 Pa	ELA	Units
	CFM/sf	Pressure (Pa)			
Armstrong Ceilings Tile	0.60	124.5	0.0642	0.0182	in2/sf
Armstrong Ceilings Lights	3.00	124.5	0.3211	0.0910	in2/sf
Armstrong Combined	0.84	124.5	0.0899	0.0255	in2/sf
FSEC(1)	3.70	25	1.1243	0.3187	in2/sf
FSEC(2)	5.50	50	1.0651	0.3019	in2/sf
ASHRAE Ceiling General			0.091	0.0260	in2/sf
ASHRAE Ceiling Dropped			0.010	0.0027	in2/sf
ASHRAE recessed lights			5.630	1.6000	in2/ea
ASHRAE for 2' by 2' light			1.408	0.4000	in2/sf
UBC 1/150 free area roof			3.378	0.9600	in2/sf

Ceiling Combined Conductance and Infiltration R-values

As described in the section on “Ceiling Leakage,” air infiltration or exfiltration is a key component of heat transfer through the ceiling plane for ceiling tiles installed on a T-bar ceiling. Air exfiltration across the ceiling plane is modeled as a two zone pressure system with the driving force being generated by the HVAC system pressurizing the conditioned space. A graphic representation of this model is shown in Figure 11.

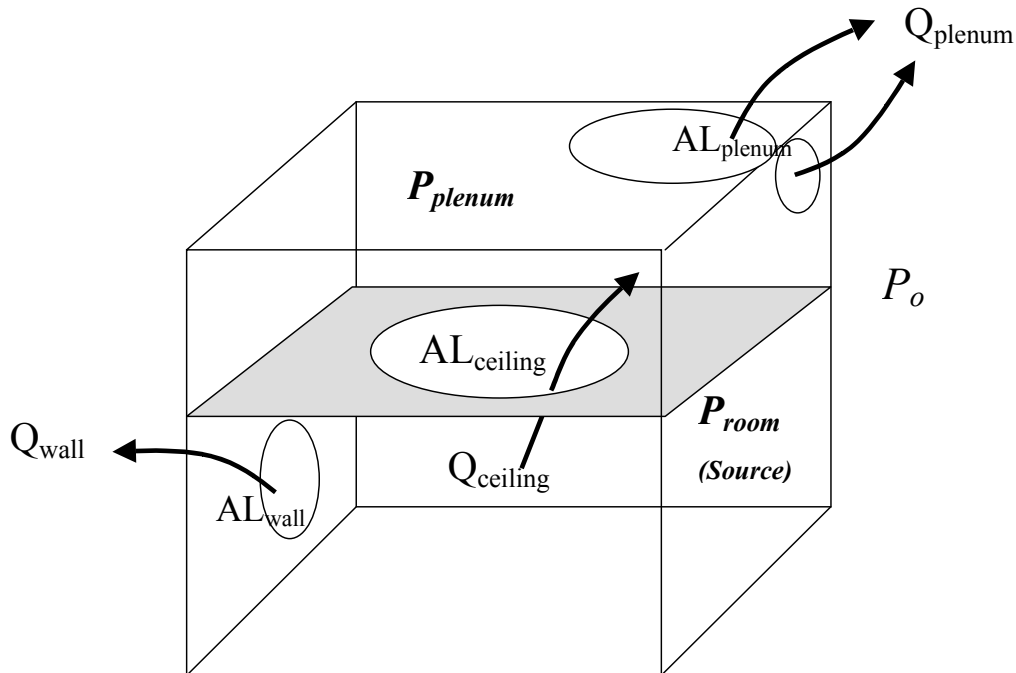


Figure 11: Pressure model to evaluate ceiling infiltration

This model assumes that HVAC induced pressures in the conditioned space act as a source and that the entire building is placed in a regime where the building is exfiltrating across all envelope surfaces. This assumption is reasonable for the summer when wind speeds are low and stack effect forces are low. In such a regime, Q_{plenum} , the flow of air exfiltrating from the walls and the roof of the plenum is equal to Q_{ceiling} , the flow of air passing from the conditioned space to the plenum through leaks in the ceiling. Given this conservation of mass of air, the following relation for volumetric flowrates of air (cubic feet per second) can be derived using a form of Bernoulli's equation.

$$Q_{\text{plenum}} = AL_{\text{plenum}} \sqrt{\frac{2 (P_{\text{plenum}} - P_o) g_c}{\rho_{\text{air}}}} = Q_{\text{ceiling}} = AL_{\text{ceiling}} \sqrt{\frac{2 (P_{\text{room}} - P_{\text{plenum}}) g_c}{\rho_{\text{air}}}}$$

where,

AL_{plenum}	=	leakage area of the plenum walls and roof, ft^2
P_{plenum}	=	pressure of the plenum, lb_f/ft^2
P_o	=	outdoor air pressure, lb_f/ft^2
g_c	=	conversion constant, $32.17 \text{ lb}_m/\text{slug}$
ρ_{air}	=	density of air, lb_m/ft^3
AL_{ceiling}	=	leakage area of the ceiling, ft^2
P_{room}	=	pressure of the room, lb_f/ft^2

If the pressures are described in terms of gauge pressure relative to the outside pressure, P_o is zero. If both sides of the equation are squared and rearranged, the pressure in the plenum, P_{plenum} , can be calculated relative to the pressure in the room, P_{room} , and the relative areas of leaks in the envelope.

$$(AL_{\text{plenum}})^2 (P_{\text{plenum}}) = (AL_{\text{ceiling}})^2 (P_{\text{room}} - P_{\text{plenum}})$$

Rearranging the terms we get:

$$[AL_{\text{plenum}}^2 + AL_{\text{ceiling}}^2] (P_{\text{plenum}}) = (AL_{\text{ceiling}})^2 (P_{\text{room}})$$

$$P_{\text{plenum}} = P_{\text{room}} \frac{AL_{\text{ceiling}}^2}{AL_{\text{plenum}}^2 + AL_{\text{ceiling}}^2}$$

Solving for flows through the roof or across the ceiling by substituting P_{plenum} .

$$Q_{plenum} = AL_{plenum} \sqrt{\frac{2 P_{room} \frac{AL_{ceiling}^2}{AL_{plenum}^2 + AL_{ceiling}^2} g_c}{\rho_{air}}}$$

or

$$Q_{ceiling} = AL_{ceiling} \sqrt{\frac{2 (P_{room} - P_{room} \frac{AL_{ceiling}^2}{AL_{plenum}^2 + AL_{ceiling}^2}) g_c}{\rho_{air}}}$$

These equations were used to develop a two zone (plenum and conditioned room) model of the 2,000 SF prototype building used for the simulations. The leakage areas for each major component in this model are specified in Table 12. Except for the FSEC values for the acoustic t-bar ceiling, all of the values come from the ASHRAE Handbook of Fundamentals.

The leakage areas in the tilt-up slab walls include a vertical joint every 8 ft. The drywall ceiling is modeled as having 5 recessed cans or other similar penetrations. When we are modeling a ventilated attic/plenum we are assuming that the roof has 1/150th of the roof area in vent openings as required by the UBC when ventilation is required. The unventilated or “tight” roof variation of the model contains raised floor leakage areas with the addition of 10 electrical or plumbing penetrations and a joint where the wall meets the roof deck. Raised floor leakage areas were used because of similar construction practices of building a continuous floor and a flat roof and the lack of other data sources. There is also a small amount of leakage area for the plenum side walls.

Table 9: Component leakage areas for 2,000 square foot prototype building

Building component	SF	Effective leakage area		Comments
		in2/ft2	SF	
Total door width	105	0.23	0.168	Door, masonry not caulked
Total window width	324	0.053	0.119	Sealed window
Sill joint	180	0.2	0.25	per lin ft
Wall	1191	0.02	0.213	Precast panel
Total wall			0.75	
Ceiling	2000	0.3	4.193	Acoustic tile
Drywall w/5 cans	2000	0.01	0.181	Drywall
Roof 1/150th free area	2000	0.96	13.33	Ventilated roof per UBC
Tight roof	2000	0.04	0.567	Roof, wall joint, 10 penetrations
Plenum side wall	540	0.02	0.097	Precast panel

The building models created out of the equations described above result in the component leakages shown in The pressure in the conditioned space, P_{room} , was varied until room air exchange rate for the building with a ventilated roof and a drywall ceiling was around 0.4 air changes per hour. This trial and error process

yielded a conditioned space gauge (relative to outside air) pressure of 0.0052 psf (025 Pascals). This same conditioned space pressure was applied to all of the other building configurations. The results of this analysis are given in Table 10.

Table 10: Flows and effective U-factors from two-zone flow analysis

Roof	Ceiling	psf Proom	psf Pplenum	ft3/s Qplenum	ft3/s Qceiling	ft3/s Qwall	ft3/s QrmTotal	Qroom ACH Total	U ceiling	Ceil CFM
Ventilated	Drywall	0.0052	9.39E-07	0.383	0.383	1.591	1.97	0.39	0.0124	23.0
Ventilated	ASHRAE T-bar	0.0052	9.79E-06	1.236	1.236	1.591	2.83	0.57	0.0401	74.2
Ventilated	FSEC t-bar	0.0052	4.62E-04	8.492	8.492	1.591	10.08	2.02	0.2751	509.5
Unventilated	Drywall	0.0052	4.58E-03	0.132	0.132	1.591	1.72	0.34	0.0043	7.9
Unventilated	ASHRAE T-bar	0.0052	5.13E-03	0.140	0.140	1.591	1.73	0.35	0.0045	8.4
Unventilated	FSEC t-bar	0.0052	5.20E-03	0.141	0.141	1.591	1.73	0.35	0.0046	8.5

Several conclusions can be drawn from the results in this table:

- Given the low leakage rates through an unventilated roof, it doesn't matter how much leakage area exists in the ceiling, the pressure in the plenum stays close to that in the conditioned space and thus the flow of air is relatively low. The model assumes that duct leaks are balanced (i.e. the leakage by supply ducts equals that of return ducts). Even if this assumption is violated, most of the air in the plenum is not lost to the outside and this air is inside of the thermal envelope.
- As shown in the second row of data in Table 10, the combination of a ventilated roof and a t-bar ceiling results in high exfiltration rates. As compared to the drywall ceiling (first row), air leakage through the t-bar ceiling increases the flows into the ceiling by a factor of 200.
- The T-bar ceiling in the second row of the table has a ceiling leakage rate of 8 cubic feet per second. This drives the overall leakage of the room so that the room loses 10 cubic feet per second. For the 9 foot tall room in the 2,000 SF building (volume = 18,000 cubic feet) this is equivalent to 2 air changes per hour as shown below:

$$ACH = \frac{10.08 \text{ ft}^3 / \text{sec} \times 3,600 \text{ sec/hr}}{18,000 \text{ ft}^3} = 2.02 \text{ air changes per hour}$$

- However, even at the high leakage rate of the T-bar ceiling, this is only 28% of the 1,722 cfm supply air flow.
- The tenth column in Table 10, gives the infiltration U-factor in units of Btu/h·ft²·°F across each ceiling.

The infiltration U-factor in units of Btu/h·ft²·°F is calculated by the relation:

$$U_{\text{infil}} = (\text{cfm/sf})(\rho_{\text{air}})(C_p)(\text{min/hr})$$

Where,

$$\text{Cfm/sf} = \text{the infiltration rate in cfm per square foot of ceiling area}$$

ρ_{air}	=	density of air, 0.075 lb _m /ft ³
C_p	=	specific heat of air, 0.24 Btu/lb _m ·°F
min/hr	=	conversion, 60 minutes per hour

As an example, the drywall ceiling (first row of Table 10) in conjunction with a ventilated attic has a flowrate of 23 cfm for our 2,000 ft² building, or 23/2,000 = 0.0115 cfm/sf. The resulting infiltration U-factor is:

$$U_{\text{infil}} = (0.0115)(0.075)(0.24)(60) = 0.0124 \text{ Btu/h}\cdot\text{ft}^2\cdot^\circ\text{F}$$

These U-factors are applied in parallel with the U-factor of the ceiling and its air films.

Total Ceiling U-factors

The total ceiling U-factor is calculated based on the U-factor of the ceiling with infiltration. The upper and lower air film U-factor is calculated based on the percentage of insulation coverage and the R-value of the air coefficients. When the ceilings are insulated (assuming foil faced batts) the top face of the ceiling has a relatively high air film thermal resistance due to the low emittance of the foil. When ceilings are uninsulated, the air film thermal resistance is lower due to the higher emittance of the ceiling tile (assumed to be 0.9). The overall U-factor of the ceiling including infiltration is then calculated by adding the U factors of the percentage of insulation, the acoustic tiles, the surface air coefficients and the infiltration U factor (see previous section). When the plenum is ventilated, two models of T-bar ceilings are used, the ASHRAE model with low infiltration rates and the FSEC model with high infiltration rate. When the plenum is unventilated, leakage across the T-bar ceiling is approximately the same for ceilings with either the FSEC or ASHRAE leakage areas. Thus a single ceiling U-factor is used to represent either the ASHRAE and FSEC ceilings in conjunction with unventilated plenums.

Table 11: U-Factors and R-Values of ventilated and unventilated ceilings with and without infiltration

Description	Roof	Ceiling	Overall-Ufactor	Infiltration U	U-factor w/ infil	R-factor with infil
Uninsulated Ceiling	Unventilated	tight T-bar	0.324	0.005	0.328	3.05
Insulated Ceiling	Ventilated	ashrae	0.046	0.040	0.087	11.56
Insulated Ceiling	Ventilated	ashrae	0.052	0.040	0.092	10.89
Insulated Ceiling	Ventilated	ashrae	0.058	0.040	0.098	10.18
Insulated Ceiling	Ventilated	ashrae	0.066	0.040	0.106	9.41
Insulated Ceiling	Ventilated	ashrae	0.077	0.040	0.117	8.57
Drywall	Ventilated	Drywall	0.043	0.012	0.056	17.94
Insulated Ceiling	Unventilated	ashrae/FSEC	0.046	0.005	0.051	19.61
Insulated Ceiling	Unventilated	ashrae/FSEC	0.052	0.005	0.056	17.76
Insulated Ceiling	Unventilated	ashrae/FSEC	0.058	0.005	0.063	15.93
Insulated Ceiling	Unventilated	ashrae/FSEC	0.066	0.005	0.071	14.12
Insulated Ceiling	Unventilated	ashrae/FSEC	0.077	0.005	0.081	12.31
Drywall	Unventilated	Drywall	0.043	0.004	0.048	20.99
Insulated Ceiling	Ventilated	FSEC	0.046	0.275	0.322	3.11
Insulated Ceiling	Ventilated	FSEC	0.052	0.275	0.327	3.06
Insulated Ceiling	Ventilated	FSEC	0.058	0.275	0.333	3.00
Insulated Ceiling	Ventilated	FSEC	0.066	0.275	0.341	2.93
Insulated Ceiling	Ventilated	FSEC	0.077	0.275	0.352	2.84

Heat Loss from Luminaires

One of the criteria for building the simulation model for our study was to account for heat loss from the luminaires, and where the heat generated from electric lighting goes, depends upon how the luminaires are mounted. In our first case study (see Section 1. Mass Building with Troffers), our models have two mounting configurations for fluorescent luminaires. Buildings that had drywall ceilings were modeled with surface mounted luminaires. Buildings with t-bar ceilings were modeled with recessed troffers. In our second and third case study (see section 2. Mass building with pendant lighting and section 3. Wood Frame Wall With Pendant Lighting), our models use pendant lighting on ceilings. We were able to obtain estimates of the fraction of heat flow from electric lighting into the plenum from Lithonia Lighting for the major classes of fluorescent luminaires. This split of lighting heat between the conditioned space and plenum is given in Table 12.

Table 12: Fraction of Electric Lighting Power to Occupied Space and Ceiling Cavity

Luminaire Mounting	Heat to occupied Space	Heat to Ceiling Cavity
Ceiling Surface Mount	90%	10%
Pendant	100%	0%
Recessed Static	70%	30%
Recessed Heat Extract	35%	65%

Thus our models of buildings with T-bar ceilings and recessed static lighting would allocate 70% of the lighting power to the conditioned space and 10% to the plenum zone. The models of buildings with a drywall ceiling and surface mounted lighting allocated 90% of the lighting heat gain to the conditioned space and just 10% to the plenum.

The fraction of lighting heat to the plenum wall versus the conditioned space is considered to be 30% for all the roof conditions except the 'drywall ceiling type' where we assume that fraction to be 10%. The section on "Heat Loss from Luminaires" describes the source of the data used for this parameter. The lighting power density used in the simulation is 1.2 W/SF, which is the prescriptive maximum for offices, and is below the 1.9 W/SF allowed in retail spaces.

Lay-in Insulation Coverage Probability Function

Site survey data collected on the fraction of ceiling coverage indicates that most buildings have between 90% and 50% insulation coverage. Since the effect of insulation coverage is likely non-linear, simulating average insulation coverage would not give an accurate estimate of energy consumption from the class of buildings containing lay-in insulation.

The energy estimating method used in this project was to simulate the energy consumption of buildings at different levels of lay-in insulation coverage. Then weighting the energy consumption of each level of insulation coverage by the probability of that insulation coverage created weighted average energy consumption for buildings with lay-in insulation.

Sorting the on-site observations into bins of insulation coverage fractions in 10% increments created estimates of insulation coverage probabilities. This sorted data is shown in the histogram in Figure 12.

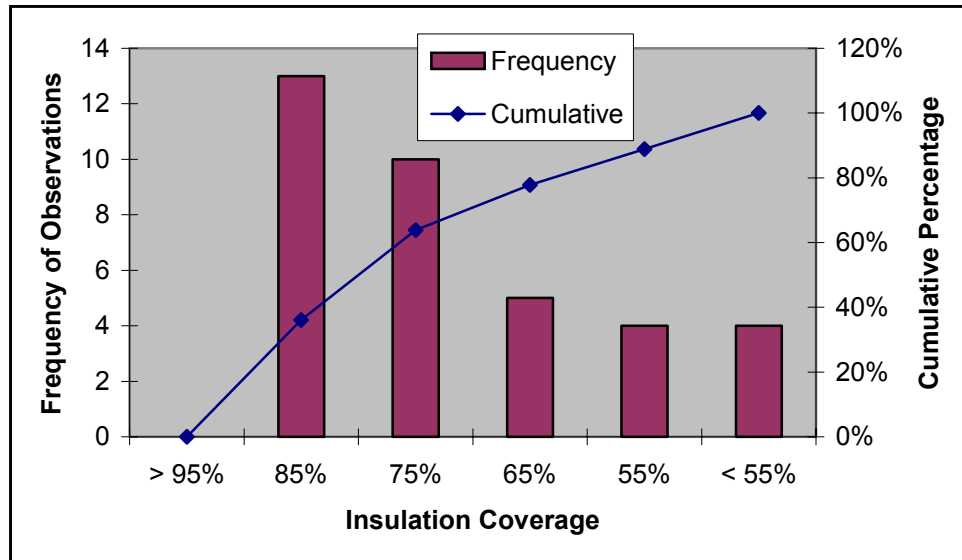


Figure 12: Insulation coverage frequency histogram

Table 13 contains the ranges of insulation coverage in each bin, the associated insulation fraction used in the model to represent this range of coverage and the probability that insulation coverage falls in a given bin. The modeled insulation fraction is the midpoint value for the bin.

Table 13: Modeled insulation fraction and probability of insulation coverage in 10% bins

Range of Insulation Coverage	Modeled Insulation	Probability Weighting
> 95%	N/A	0%
95% to 85%	90%	36%
85% to 75%	80%	28%
75% to 65%	70%	14%
65% to 55%	60%	11%
< 55%	50%	11%

This probability distribution is perhaps somewhat conservative in that the two observations (10% of observations) with only 10% insulation coverage are lumped into the '<55% coverage' category and are modeled with 50% insulation coverage. To identify the impacts of this conservative assumption, an initial study performed some simulations with 10% insulation coverage added to the probability distribution. The analysis on these simulations indicated a very small change in the benefit cost ratio when compared to the results where these outliers were added to the <55% coverage grouping of coverage and the entire grouping was modeled as having 50% coverage.

RESULTS

This section describes the results of whole building energy analysis and applied to the life cycle costing and benefit to cost analysis. These results are based on:

- Cooling loads: These are the building loads at the cooling coil. The total site energy impact of measures must also consider the coefficient of performance of the air conditioner.
- Heating loads: These are the building loads at the heat exchange of the gas furnace, the total site energy impacts would result from applying the combustion efficiency of furnace to these heating loads.
- TDV savings: This metric compares the life cycle energy cost savings of a given building configuration to a base case. In most of these analyses, the base case is a building with an uninsulated roof and T-bar ceiling insulated with lay-in insulation. The time dependent valuation places a high monetary value on electricity during times of high statewide consumption such as hot summer afternoons. Time dependent valuation is the metric of choice when evaluating the life cycle cost energy cost savings of energy code measures. The hourly energy costs embedded in TDV account for the costs of energy and peak demand. Thus measures that reduce the air conditioning during high periods are given credit for energy savings and peak electrical demand reductions. For this type of analysis, the TDV factors are based on a period of analysis of 30 years and a 3% discount rate.
- Benefit cost ratio: This is the ratio of the TDV energy cost savings to the incremental first cost. The TDV cost savings is the reduction in TDV energy costs of a given building configuration relative to the base building (usually with lay-in insulation on a suspended acoustic tile ceiling). The incremental first costs of a given building configuration are those first costs of the building minus the first cost of the base case building (covered with lay-in insulation on T-bar ceiling).

Analyses were conducted for three building types:

- Mass wall with recessed troffers
- Mass wall with suspended pendant lighting
- Wood frame wall with suspended pendant lighting

1. Mass Building with Troffers

Description of Building Parameters

This building study consists of an 8" thick tilt up concrete wall. The Building is a single story office space with an area of 2000sqft, using office occupant densities, internal loads and schedules. Six climate zones were considered for the roof insulation analysis- CTZ3, CTZ6, CTZ10, CTZ12 and CTZ14.

1. The building parametric runs had 6 different types of roofing insulation conditions in conjunction with an unventilated plenum. Though we have considered two levels of T-bar ceiling infiltration leakage areas, when the plenum is unventilated, the movement of air through the ceiling is limited by the leakage of the roof. Thus, there is little difference between the higher leakage area (FSEC) ceiling and the lower leakage area (ASHRAE) ceiling and they are treated as equivalent. These parametric runs are:

- "Under deck plenum insul.": insulated roof with **insulated** plenum walls and an uninsulated T-bar ceiling.
- "Under deck plenum uninsul.": insulated roof with **uninsulated** plenum walls and an uninsulated t-bar ceiling.
- "Above deck plenum insul.": insulated roof with **insulated** plenum walls and an uninsulated t-bar ceiling.
- "Above deck plenum uninsul.": insulated roof with **uninsulated** plenum walls and an uninsulated t-bar ceiling.
- "Drywall ceiling-UV" : uninsulated roof deck and **uninsulated** plenum walls with an insulated drywall (low infiltration leakage area) ceiling.
- "Lay-in unventilated" : uninsulated roof deck and **uninsulated** plenum walls with an average of 50-90% insulation coverage of the t-bar ceiling area.

2. The building parametric runs had 3 different types of roofing insulation conditions in conjunction with a ventilated plenum. Note the insulated roof deck cases are not included in this set of parametrics. If the thermal boundary is at the roof level, ventilating the plenum would violate the infiltration integrity of the conditioned space. The flow of air through the ceiling is substantially different between the higher leakage area (FSEC) ceiling and the lower leakage area (ASHRAE) ceiling and thus they are simulated separately. The parametrics with a ventilated plenum are:

- "Drywall ceiling-V" : uninsulated roof deck and **uninsulated** plenum walls with an insulated drywall (low infiltration leakage area) ceiling.

- “Lay-in ASHRAE ventilated ” : uninsulated roof deck and **uninsulated** plenum walls with an average of 50-90% insulation coverage of the t-bar ceiling area. Air leakage through the ceiling uses the lower ASHRAE infiltration values.
 - “Lay-in FSEC” : uninsulated roof deck and **uninsulated** plenum walls with an average of 50-90% insulation coverage of the t-bar ceiling area. Air leakage through the ceiling uses the higher FSEC infiltration values.
3. In order to study the effect of duct leakage on the effectiveness of lay-in insulation and vice versa, all of the above insulation parameters will be evaluated with a low leakage (8% leaks – 4% supply and 4% return leaks) duct system and with high leakage (36%) ducts.
 4. Two types of duct insulation were used in the models— R 4.2 and R 8. The current code requirements are for R 4.2 but R 8 is being considered for the new efficiency standards¹⁴.
 5. The effect of five different plenum heights is also analyzed. The plenum heights included in the study are 3', 6', 9', 12' and 15'. It is expected that plenum height is a key determinant of the relative performance of T-bar and insulated roofs.

Analysis

The analysis of the simulation results was done based on cooling loads, heating loads, TDV savings and benefit cost ratio.

Effects of Insulation Location on Cooling Loads

The total cooling loads (kBtu/sq-ft) were plotted for the various insulation conditions that were simulated using the DOE-2 model. The results of two climate zones, 3 and 12, with leaky duct (R 4.2) situation are described below. The graphs of cooling and heating loads for tight ducts (R8) are shown in the Appendix A. It was observed that the cooling and heating loads of all insulating conditions for tight ducts showed comparable patterns with the cooling and heating loads for the leaky ducts.

Climate Zone 3

The location of the insulation on the roof deck versus the ceiling showed the following results on the total cooling loads of the building. In reviewing the results, it helps to remember that these small systems do not have an economizer.

- As the plenum height increases from 3 feet to 15 feet, there is a decrease in the total cooling loads for all the various insulation conditions. As the plenum height increases, the area of the mass plenum walls also increases, and thus

¹⁴ 2005 Title 24 Proposed Building Energy Efficiency Standards

there is more thermal mass to shift the cooling loads to after hours when the HVAC system is turned off.

- The unventilated drywall insulated ceiling showed maximum cooling loads when compared to the rest of the insulation conditions. This could be attributed to the fact that not ventilating the plenum space prevents the heat loss from the conditioned space and hence increases the cooling loads on the building.
- The cooling loads for the two roof deck insulation conditions (above deck and under deck) with plenum walls uninsulated had the lowest values for the cooling loads as compared to the other insulation conditions (both showed almost the same cooling loads). When comparing the insulated roof decks, the ones with plenum wall insulated had higher cooling loads than the ones with uninsulated plenum walls. Insulating the roof deck deflects solar loads through the roof and keeps mass plenum wall cool. Insulating the mass wall makes it unavailable for thermal mass to shift the cooling loads.
- The three ventilated ceiling insulation conditions (drywall, FSEC, ASHRAE) had lower cooling loads than the unventilated dry wall insulation conditions. The FSEC results indicate lower cooling loads than dry wall or ASHRAE lay-in condition. This could be attributed to higher infiltration rates for FSEC values with a mild climate zone.

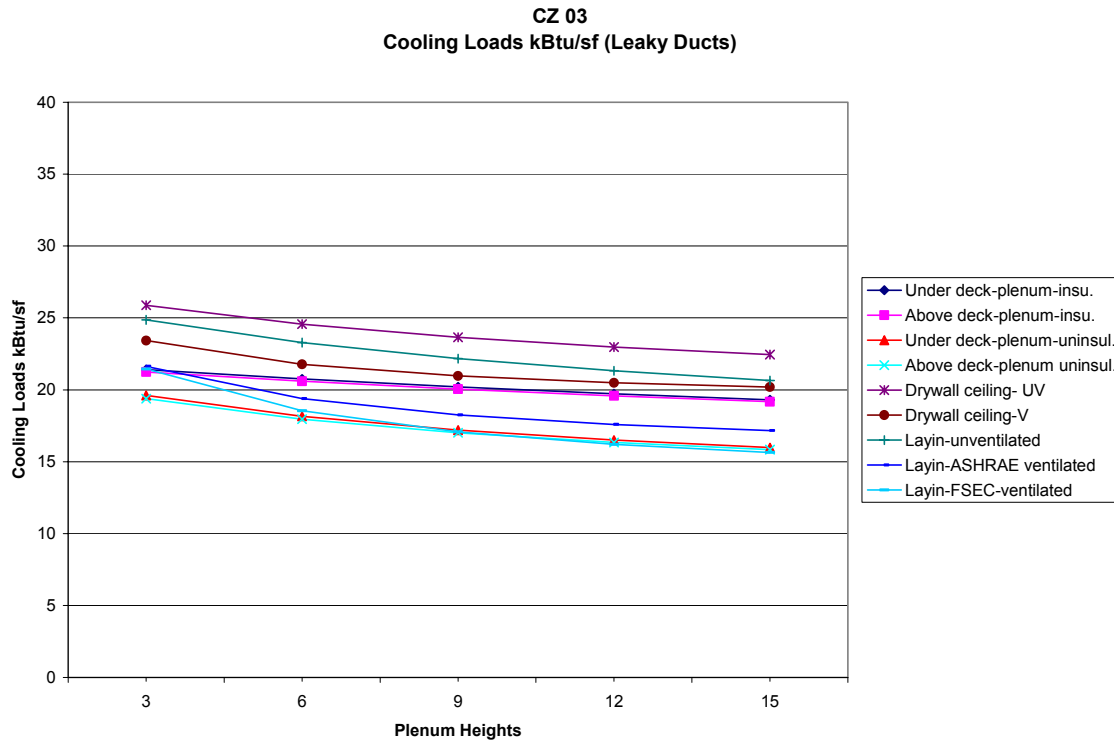


Figure 13: Cooling loads (kBtu/sq ft) varying with plenum heights for Climate Zone 3

Climate Zone 12

Increase in the plenum height makes little change on the cooling loads in the building for this climate zone.

- The four conditions of insulated roof decks have lower cooling loads than the insulated ceilings. The above deck and under deck roof conditions with uninsulated plenum walls have lower cooling loads than the above and under deck roof conditions with insulated plenum walls.
- Among the insulated ceilings, the unventilated insulated drywall and lay-in ceilings indicate maximum cooling loads when compared to the rest of the insulated ceilings. Ventilated and insulated drywall, ASHRAE and FSEC ceilings indicate comparable cooling loads.

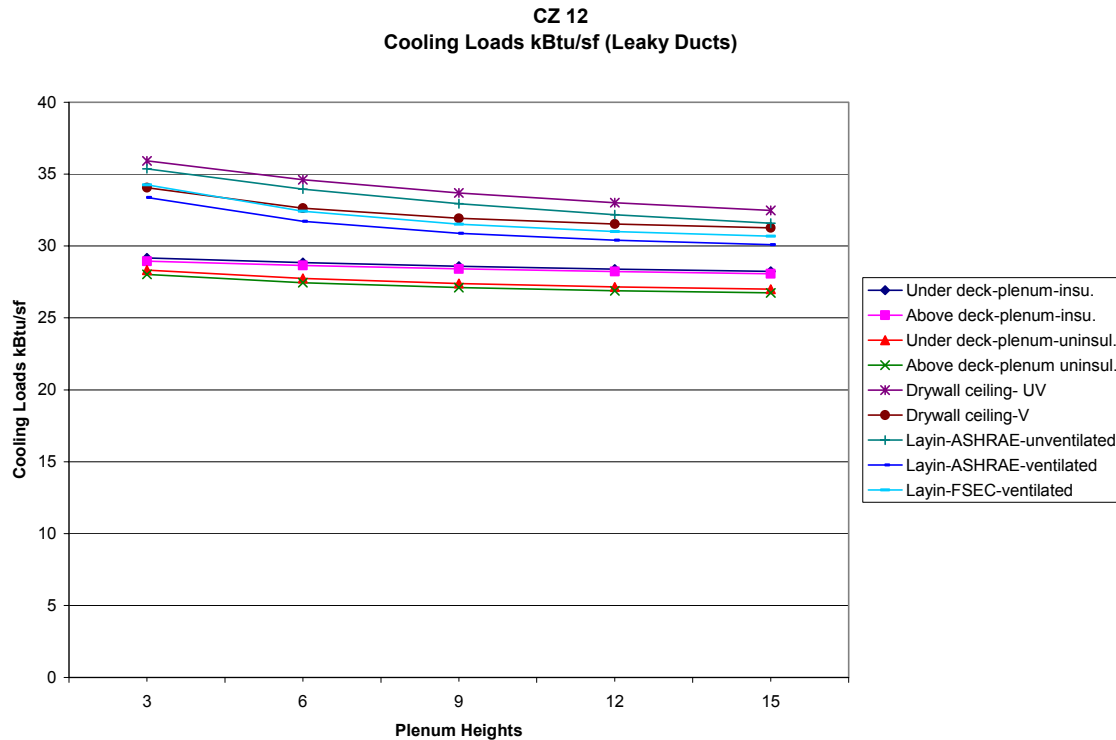


Figure 14: Cooling loads (kBtu/sq ft) varying with plenum heights - Climate Zone 12

Effects of Insulation Position on Heating Loads

Climate Zone 3

- The heating loads increase with increase in plenum heights for all insulation conditions. With increase in plenum height, the volume of plenum space also increases, which results in higher CFM rates and higher infiltration to conditioned space and hence the need for more heating. Since the ventilated attic cases have a fixed number of air changes, increasing the plenum height increases the volumetric flow of the plenum. This increases heating loads in two ways: the regain to the conditioned space is decreased, temperature of the plenum is decreased resulting in more heating loads.
- Maximum heating loads were observed for FSEC ventilated lay-in insulated (attributed to the high ventilation rates), followed by ASHRAE ventilated lay-in ceiling. Minimum heating loads were observed in unventilated and insulated drywall ceiling condition.
- The insulated roofs (under deck and above deck) with uninsulated plenum walls had higher heating loads than the ventilated drywall ceiling. This is attributed to the heat loss due to uninsulated plenum walls. The under deck and above deck roofs with insulated plenum walls and the unventilated drywall ceiling had the lowest heating loads when compared to the other insulation conditions.

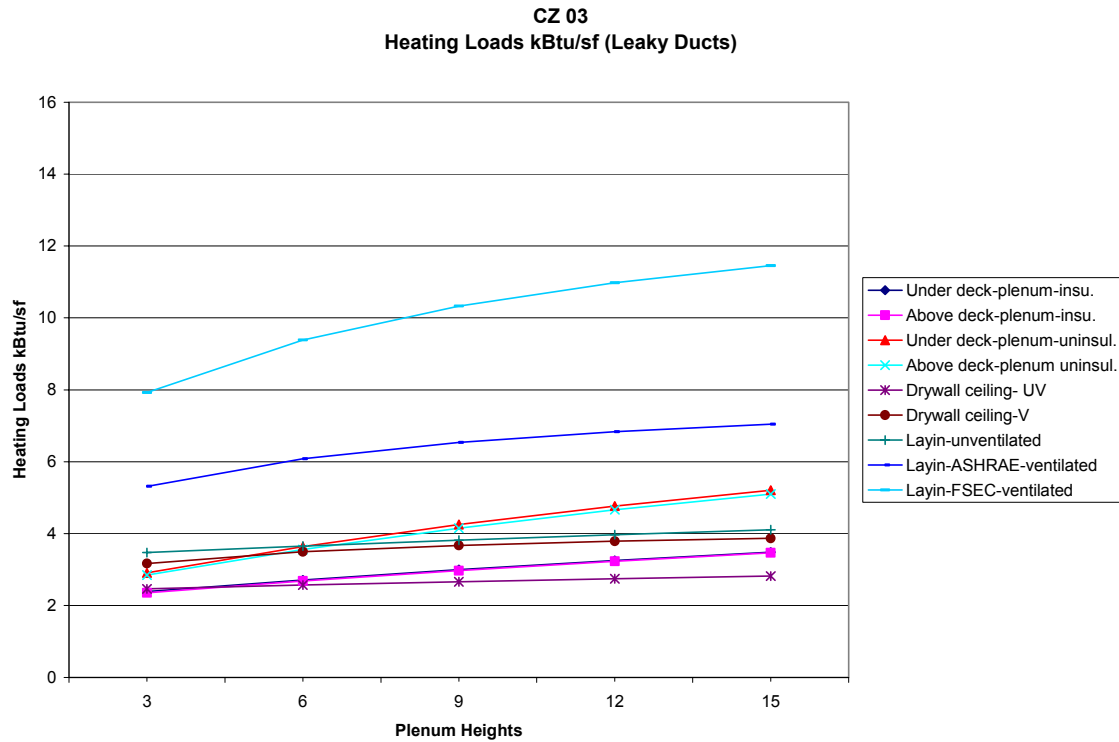


Figure 15: Heating loads varying with plenum heights- Climate Zone 3

Climate Zone 12

The heating loads pattern for climate zone 12 was observed to be similar to that of climate zone 3, except that ventilated and insulated drywall indicates higher heating loads than insulated roofs with insulated plenum walls. This indicates the relative impact of infiltration losses to conductive losses as the climate gets more extreme.

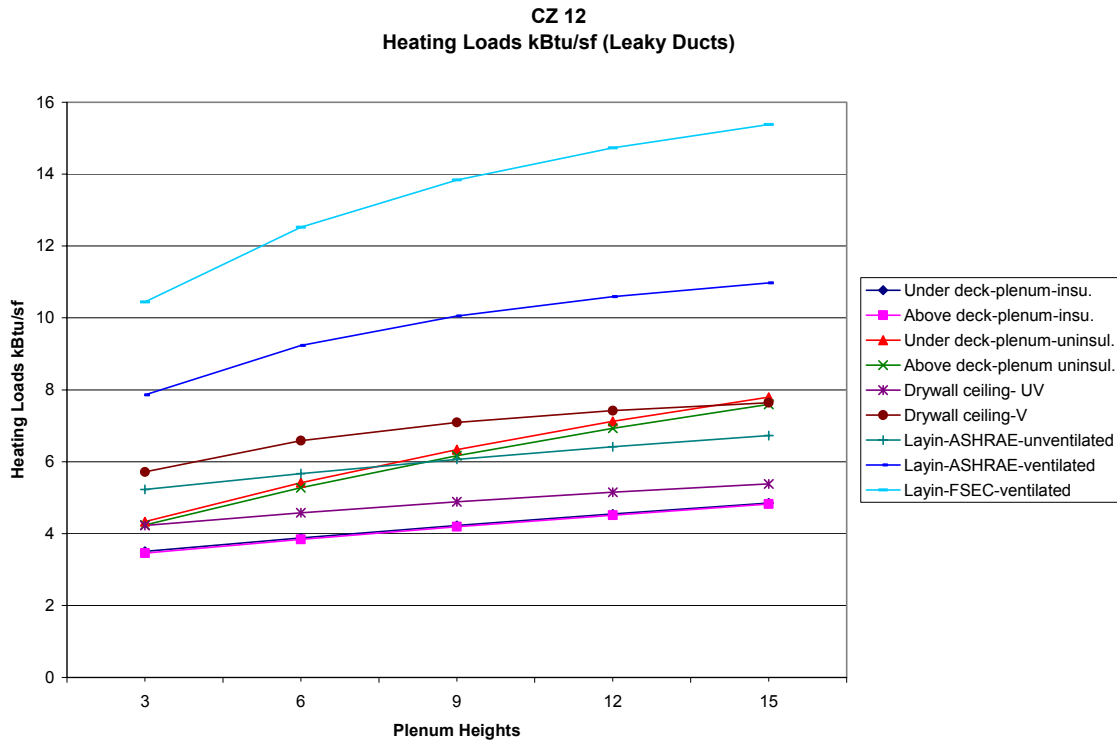


Figure 16: Heating loads varying with plenum heights- Climate Zone 12

Effects of Insulation Position on TDV Savings

The TDV savings for insulated roof decks drywall ceiling were analyzed based on the lay-in insulated and ventilated acoustic tile ceilings using both the ASHRAE and FSEC values of ventilation rates. The TDV savings for climate zone 3 and 12 with leaky ducts is described below.

Climate Zone 3

- The TDV savings decrease with the increase in the plenum heights for all insulation conditions. The savings with FSEC values indicate higher TDV savings when compared to ASHRAE values.
- The roof decks with uninsulated plenum walls showed maximum TDV savings of which the one with the above deck roof conditions had the maximum value. This could be attributed to these conditions having lower cooling loads than the other insulated roofs/ceilings.
- Both the ventilated and unventilated drywall ceilings indicate negative TDV savings. In case of unventilated drywall condition, the savings increase with increase in plenum heights.
- The higher the plenum height, the less regain of heating or cooling lost by ducts. Since attic ventilation is a constant air exchange per hour, higher

plenums result in more CFM of outside air. This dilutes the air lost by ducts that are cooling (in summer) and heating (in winter) the ventilated plenum.

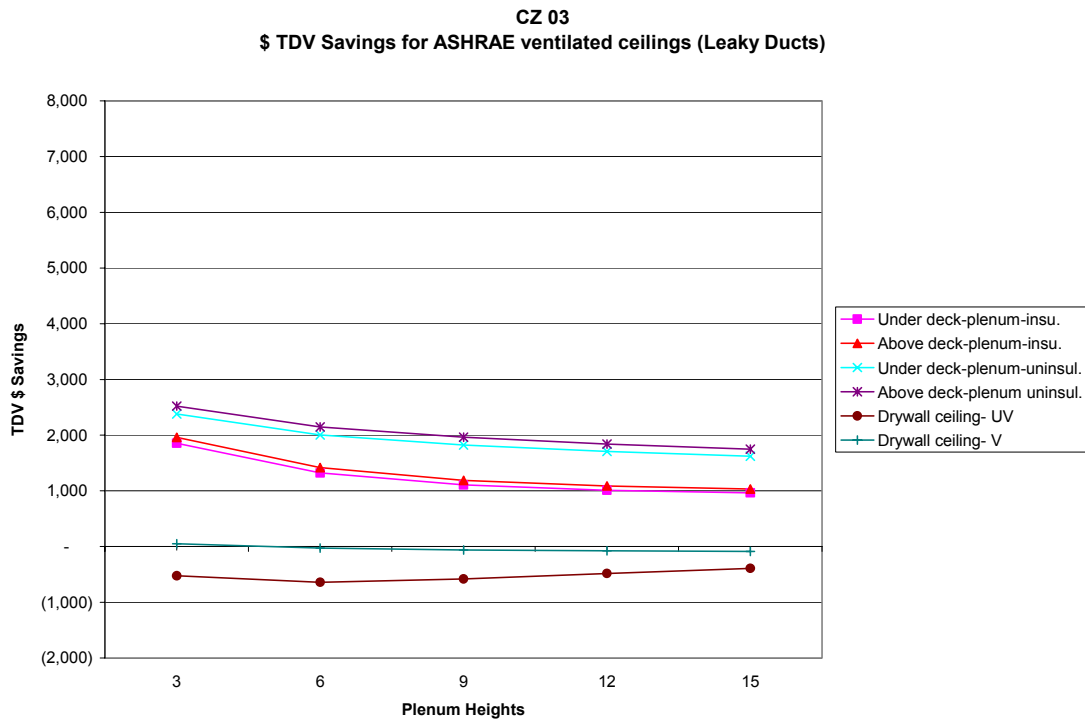


Figure 17: TDV savings with varying plenum heights (ASHRAE ventilation rates),
Climate Zone 3

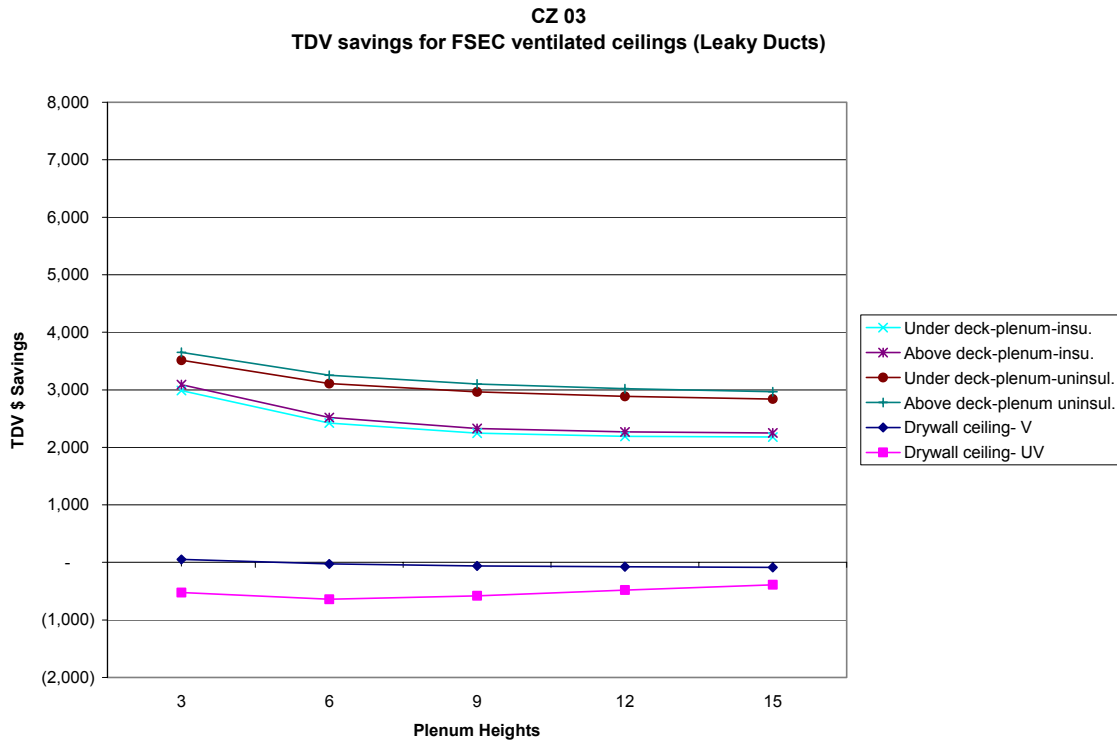


Figure 18: TDV savings with varying plenum heights (FSEC ventilation rates), Climate Zone 3

Climate Zone 12

- In the ASHRAE infiltration model, as plenum height increases, there is a decrease in TDV costs for insulated roofs. In FSEC model, the roofs with insulated plenum have increasing TDV with increase in plenum heights, while roofs with uninsulated plenum indicate decrease in TDV savings with increasing plenum heights. This shows the trade-off between duct regain, thermal mass and conduction effects.
- The insulated drywall ceiling (ventilated and unventilated) indicates an increase in TDV savings with increase in plenum heights.

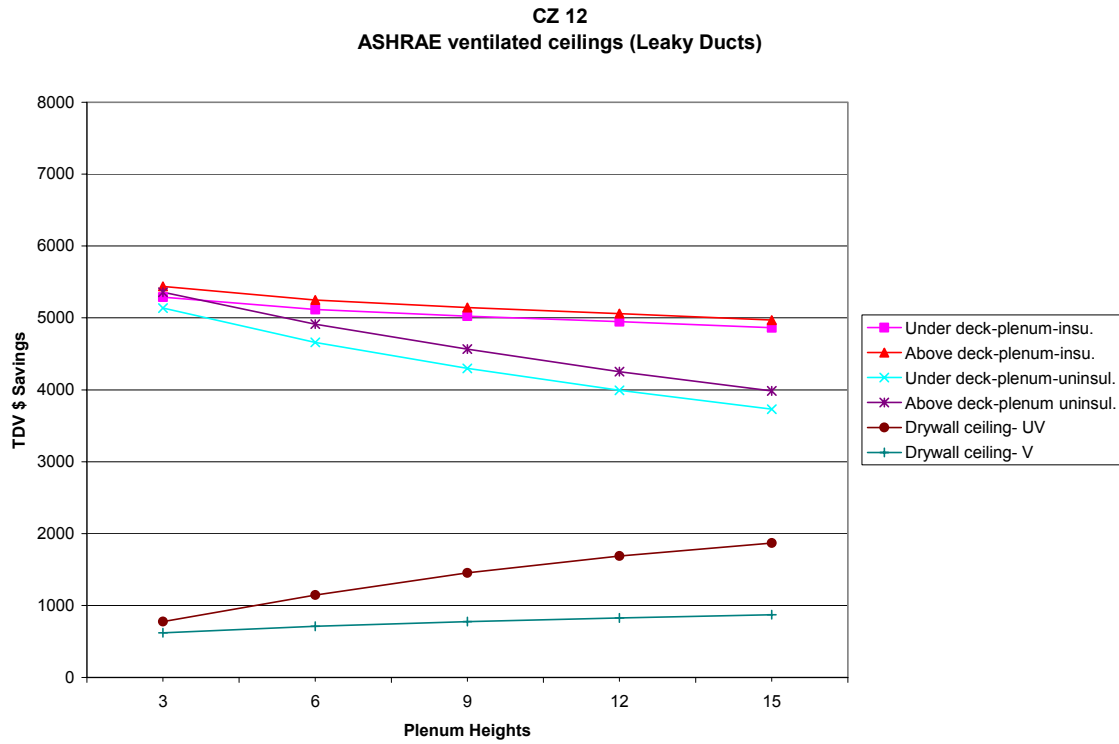


Figure 19: TDV savings with varying plenum heights (ASHRAE ventilation rates), Climate Zone 12

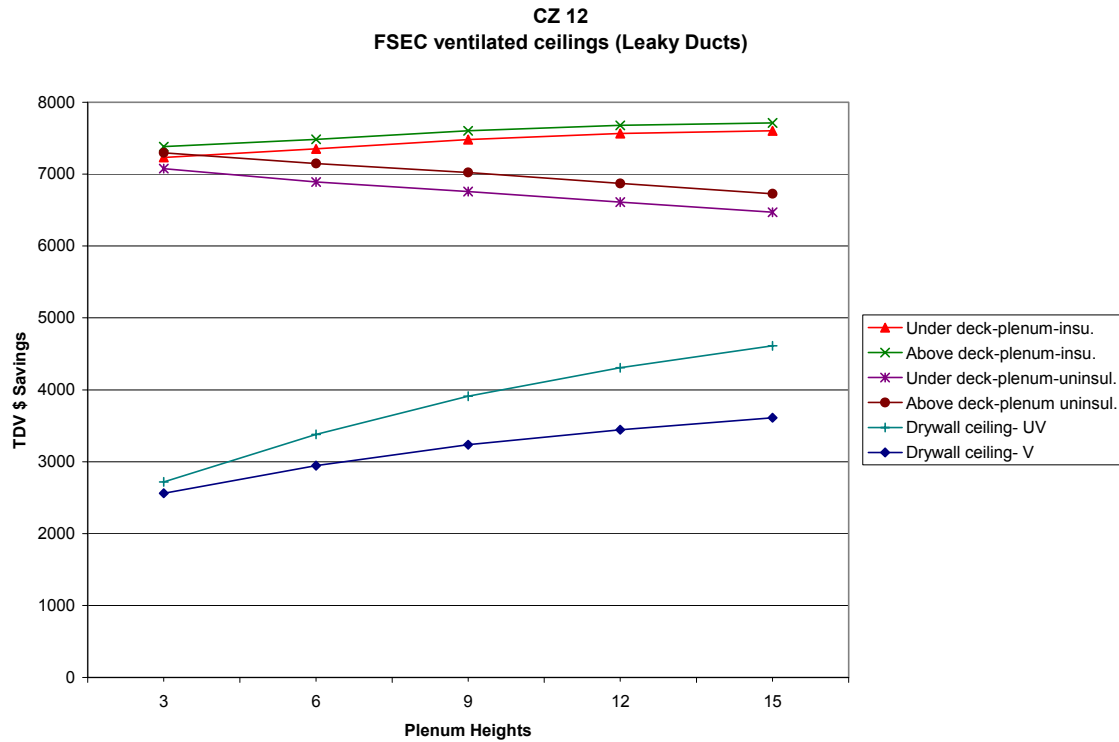


Figure 20: TDV savings with varying plenum heights (FSEC ventilation rates), Climate Zone 12

Measure Costs

Interviews with contractors were conducted to get the latest pricing information for the types of insulations and ceilings considered in the study. As a reference, the RS Means Building Construction Cost Data, 15th Annual Edition, 2002 Western Edition, was used as an industry standard to obtain pricing information.

The lookup tables in the Means Catalogue provide an average cost for many typical construction materials and methods. To make a sound comparison with the cost data obtained from the contractors, the data obtained was adjusted from the lookup tables using RS Means city cost indexes that provide the average cost for 20 cities. An average of the city indexes was applied for the cities of Sacramento, Stockton, Vallejo, San Diego, Los Angeles, and San Jose to adjust the look up table values. The city index (shown in Table 14) is a percent ratio of the specific city's cost to the 20 city average cost of the same item at the same stated time period. The average for the six cities considered was approx.111.0.

Table 14: City Cost Indexes

City	Cost Index from RS Means Catalogue
Sacramento	109.8
Stockton	108.7
Vallejo	114.0
San Diego	105.4
Los Angeles	108.0
San Jose	120.0
Average	111.0

The costs presented for each survey includes the cost of materials, labor and the contractors overheads and profits. The interviewees were asked to give a percent value of labor in the cost they reported. Some of the contractors refused to give out this information due to competitive reasons, and hence are not reported. A detailed cost estimate is provided as a table in Appendix C.

Table 15: Cost estimates (\$) of insulation on roof decks and ceilings for climate zones 3, 6, 10, 12, 14

CZ 03

	Lay-in insulation on Acoustic Tiles	Lay-in insulation on Drywall ceiling	Uninsulated plenum walls, non-rigid insulation under metal deck	Uninsulated plenum walls, rigid insulation above metal deck	Insulated plenum walls (conc), non-rigid insulation under metal deck	Insulated plenum walls (conc), rigid insulation above metal deck	Insulated plenum walls (framed), non-rigid insulation under metal deck	Insulated plenum walls (framed), rigid insulation above metal deck
Plenum 3'	\$5,050	\$7,895	\$5,639	\$7,091	\$6,053	\$7,505	\$5,943	\$7,396
Plenum 6'	\$5,050	\$7,895	\$5,639	\$7,091	\$6,467	\$7,919	\$6,248	\$7,700
Plenum 9'	\$5,050	\$7,895	\$5,639	\$7,091	\$6,881	\$8,333	\$6,553	\$8,005
Plenum 12'	\$5,050	\$7,895	\$5,639	\$7,091	\$7,295	\$8,747	\$6,857	\$8,310
Plenum 15'	\$5,050	\$7,895	\$5,639	\$7,091	\$7,709	\$9,161	\$7,162	\$8,614

CZ 06

	Lay-in insulation on Acoustic Tiles	Lay-in insulation on Drywall ceiling	Uninsulated plenum walls, non-rigid insulation under metal deck	Uninsulated plenum walls, rigid insulation above metal deck	Insulated plenum walls, non-rigid insulation under metal deck	Insulated plenum walls, rigid insulation above metal deck	Insulated plenum walls (framed), non-rigid insulation under metal deck	Insulated plenum walls (framed), rigid insulation above metal deck
Plenum 3'	\$4,796	\$7,641	\$5,425	\$5,970	\$5,839	\$6,384	\$5,730	\$6,275
Plenum 6'	\$4,796	\$7,641	\$5,425	\$5,970	\$6,253	\$6,798	\$6,035	\$6,579
Plenum 9'	\$4,796	\$7,641	\$5,425	\$5,970	\$6,667	\$7,212	\$6,339	\$6,884
Plenum 12'	\$4,796	\$7,641	\$5,425	\$5,970	\$7,081	\$8,040	\$6,644	\$7,189
Plenum 15'	\$4,796	\$7,641	\$5,425	\$5,970	\$7,495	\$8,040	\$6,949	\$7,493

CZ 10, 12, 14

	Lay-in insulation on Acoustic Tiles	Lay-in insulation on Drywall ceiling	Uninsulated plenum walls, non-rigid insulation under metal deck	Uninsulated plenum walls, rigid insulation above metal deck	Insulated plenum walls, non-rigid insulation under metal deck	Insulated plenum walls, rigid insulation above metal deck	Insulated plenum walls (framed), non-rigid insulation under metal deck	Insulated plenum walls (framed), rigid insulation above metal deck
Plenum 3'	\$5,050	\$7,895	\$5,639	\$7,091	\$6,094	\$7,546	\$5,967	\$7,420
Plenum 6'	\$5,050	\$7,895	\$5,639	\$7,091	\$6,549	\$8,002	\$6,296	\$7,748
Plenum 9'	\$5,050	\$7,895	\$5,639	\$7,091	\$7,005	\$8,457	\$6,625	\$8,077
Plenum 12'	\$5,050	\$7,895	\$5,639	\$7,091	\$7,460	\$8,913	\$6,953	\$8,406
Plenum 15'	\$5,050	\$7,895	\$5,639	\$7,091	\$7,916	\$9,368	\$7,282	\$8,734

The additional cost required to insulate the ducts from R4.2 to R8 along with the cost of tightening the ducts (a total addition of \$600) for all the given insulation conditions were estimated as given below in Table 16.

Table 16: Cost estimates (\$) of insulation on roof decks and ceilings along with cost of insulating and tightening ducts for climate zones 3, 6, 10, 12, 14

	Lay-in insulation on Acoustic Tiles	Lay-in insulation on Drywall ceiling	Uninsulated plenum walls, non-rigid insulation under metal deck	Uninsulated plenum walls, rigid insulation above metal deck	Insulated plenum walls (conc), non-rigid insulation under metal deck	Insulated plenum walls (conc), rigid insulation above metal deck	Insulated plenum walls (framed), non-rigid insulation under metal deck	Insulated plenum walls (framed), rigid insulation above metal deck
Plenum 3'	\$5,650	\$8,495	\$6,239	\$7,691	\$6,653	\$8,105	\$6,543	\$7,996
Plenum 6'	\$5,650	\$8,495	\$6,239	\$7,691	\$7,067	\$8,519	\$6,848	\$8,300
Plenum 9'	\$5,650	\$8,495	\$6,239	\$7,691	\$7,481	\$8,933	\$7,153	\$8,605
Plenum 12'	\$5,650	\$8,495	\$6,239	\$7,691	\$7,895	\$9,347	\$7,457	\$8,910
Plenum 15'	\$5,650	\$8,495	\$6,239	\$7,691	\$8,309	\$9,761	\$7,762	\$9,214

CZ 06

	Lay-in insulation on Acoustic Tiles	Lay-in insulation on Drywall ceiling	Uninsulated plenum walls, non-rigid insulation under metal deck	Uninsulated plenum walls, rigid insulation above metal deck	Insulated plenum walls, non-rigid insulation under metal deck	Insulated plenum walls, rigid insulation above metal deck	Insulated plenum walls (framed), non-rigid insulation under metal deck	Insulated plenum walls (framed), rigid insulation above metal deck
Plenum 3'	\$5,396	\$8,241	\$6,025	\$6,570	\$6,439	\$6,984	\$6,330	\$6,875
Plenum 6'	\$5,396	\$8,241	\$6,025	\$6,570	\$6,853	\$7,398	\$6,635	\$7,179
Plenum 9'	\$5,396	\$8,241	\$6,025	\$6,570	\$7,267	\$7,812	\$6,939	\$7,484
Plenum 12'	\$5,396	\$8,241	\$6,025	\$6,570	\$7,681	\$8,226	\$7,244	\$7,789
Plenum 15'	\$5,396	\$8,241	\$6,025	\$6,570	\$8,095	\$8,640	\$7,549	\$8,093

CZ 10, 12, 14

	Lay-in insulation on Acoustic Tiles	Lay-in insulation on Drywall ceiling	Uninsulated plenum walls, non-rigid insulation under metal deck	Uninsulated plenum walls, rigid insulation above metal deck	Insulated plenum walls, non-rigid insulation under metal deck	Insulated plenum walls, rigid insulation above metal deck	Insulated plenum walls (framed), non-rigid insulation under metal deck	Insulated plenum walls (framed), rigid insulation above metal deck
Plenum 3'	\$5,650	\$8,495	\$6,239	\$7,691	\$6,694	\$8,146	\$6,567	\$8,020
Plenum 6'	\$5,650	\$8,495	\$6,239	\$7,691	\$7,149	\$8,602	\$6,896	\$8,348
Plenum 9'	\$5,650	\$8,495	\$6,239	\$7,691	\$7,605	\$9,057	\$7,225	\$8,677
Plenum 12'	\$5,650	\$8,495	\$6,239	\$7,691	\$8,060	\$9,513	\$7,553	\$9,006
Plenum 15'	\$5,650	\$8,495	\$6,239	\$7,691	\$8,516	\$9,968	\$7,882	\$9,334

Benefit Cost Ratio

The benefit cost analysis was done based on the TDV savings and the difference in the material costs of all the roofing insulation options as compared to lay-in insulation costs (as described in first part of the section). The following tables show the benefit cost ratios for climate zone 3 and 12, along with a summary of benefit cost ratios of all the five climate zones under study. The benefit cost ratios for climate zones 6, 10, and 14 are shown in Appendix A. The naming convention used in the following benefit cost ratio tables is described in Table 17.

Table 17: Description of naming convention used in the Benefit Cost Ratio Tables

Name	Description
Under deck-plenum-insu.	Under deck insulated roof with insulated plenum walls and an uninsulated t-bar ceiling
Above deck-plenum-insu.	Above deck insulated roof with insulated plenum walls and an uninsulated t-bar ceiling
Under deck-plenum-uninsul.	Under deck insulated roof with uninsulated plenum walls and an uninsulated t-bar ceiling
Above deck-plenum-uninsul.	Above deck insulated roof with uninsulated plenum walls and an uninsulated t-bar ceiling
Drywall ceiling -UV	Uninsulated roof deck and uninsulated plenum walls with an insulated drywall (low infiltration leakage area) ceiling-Unventilated
Drywall ceiling -V	Uninsulated roof deck and uninsulated plenum walls with an insulated drywall (low infiltration leakage area) ceiling-Ventilated
Lay-in -UV	Uninsulated roof deck and uninsulated plenum walls with average value of 90%-50% of the t-bar ceiling area insulated with unventilated plenum
Lay-in -V	Uninsulated roof deck and uninsulated plenum walls with average value of 90%-50% of the t-bar ceiling area insulated with ventilated plenum

1. Benefit cost ratios of sealing and insulating ducts for insulated roofs, drywall and lay-in ceilings

Table 18 shows the benefit cost ratios for tightening the ducts and adding duct insulation (from R 4.2 to R 8) for insulated roof deck, drywall and lay-in ceiling conditions for climate zone 3 and 12. The benefit cost ratios were calculated for the plenum heights of 3ft, 6ft, 9ft, 12ft and 15ft. The calculations were based on the difference between the total TDV costs of all insulation conditions with leaky ducts to all insulation conditions with tight ducts. This value was then divided by the cost of adding insulation and sealing the ducts.

The primary conclusion to draw from this table is that sealing ducts is cost effective for all ceilings and roof decks with uninsulated plenum walls. It is not cost effective or marginally cost effective to seal and insulate ducts for insulated roofs with insulated plenums.

Table 18: Benefit cost ratio of sealing ducts and increasing duct insulation from R 4.2 to R 8, Climate Zone 3

CTZ3 Benefit cost for Tightening Ducts for all insulation conditions									
Plenum Hts	Insulated Plenum Wall		Uninsulated Plenum Wall						
	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.	Drywall ceiling- UV	Drywall ceiling- V	Lay-in- UV	Lay-in-V ASHRAE	Lay-in-V- FSEC
3	0.66	0.61	0.89	0.81	3.33	3.62	2.85	3.50	3.02
6	0.81	0.76	1.15	1.05	3.18	3.41	2.88	3.61	3.52
9	0.93	0.89	1.36	1.24	3.05	3.28	2.89	3.64	3.83
12	1.05	1.01	1.53	1.42	2.93	3.21	2.88	3.67	4.03
15	1.15	1.11	1.69	1.57	2.85	3.16	2.87	3.69	4.18

Table 19 shows the benefit cost ratios for tightening the ducts and adding duct insulation (from R 4.2 to R 8) for insulated roof deck, drywall and lay-in ceiling conditions for climate zone 12. This climate zone indicates cost effectiveness for mostly all insulation conditions and for all plenum heights.

Table 19: Benefit cost ratio of sealing ducts and increasing duct insulation from R 4.2 to R 8, Climate Zone 12

CTZ12 Benefit costs of tightening the ducts for all insulation conditions									
Plenum Hts	Insulated Plenum Wall		Uninsulated Plenum Wall						
	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.	Drywall ceiling- UV	Drywall ceiling- V	Lay-in- UV	Lay-in-V ASHRAE	Lay-in-V- FSEC
3	0.87	0.79	1.31	1.15	5.72	7.36	4.90	6.75	5.58
6	1.07	1.01	1.96	1.73	5.93	7.94	5.28	7.87	7.28
9	1.27	1.20	2.51	2.24	6.06	8.25	5.55	8.46	8.30
12	1.43	1.36	3.00	2.73	6.15	8.45	5.79	8.85	8.97
15	1.62	1.55	3.44	3.16	6.23	8.58	5.97	9.13	9.46

Table 20 shows the summary of benefit cost ratios for tightening ducts for climate zones 3, 6, 10, 12 and 14 based on which plenum heights show cost effectiveness. In Table 18, 'None' represents no benefit costs for any of the plenum heights (3ft, 6ft, 9ft, 12ft and 15ft), 'All' represents cost effectiveness for all plenum heights, >3', >6' and >9' represents cost effectiveness above 3 feet, 6 feet and 9 feet of plenum height. Most insulation conditions indicate cost effectiveness in tightening the ducts.

Table 20: Summary of cost effectiveness of tightening ducts for insulated roofs, and drywall and lay-in ceilings for climate zones 3, 6, 10, 12 and 14

Summary-Cost effectiveness of tightening ducts									
Climate Zones	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum-uninsul.	Drywall ceiling- UV	Drywall ceiling- V	Lay-in-UV	Lay-in-V-ASHRAE	Lay-in-V-FSEC
CTZ3	>9	>9	>3	>3	All	All	All	All	All
CTZ6	>3	>3	All	All	All	All	All	All	All
CTZ10	All	>3	All	All	All	All	All	All	All
CTZ12	>3	>3	All	All	All	All	All	All	All
CTZ14	All	All	All	All	All	All	All	All	All

2. Benefit cost ratio of insulated roof decks with leaky ducts (R 4.2) versus insulated lay-in ceiling with tight ducts (R 8), Climate zone 3

The second case determines the benefit cost ratios for insulated roof deck conditions with leaky ducts (with R4.2 duct insulation) versus insulated lay-in ceilings with tight ducts (with R 8 duct insulation) for both ASHRAE and FSEC values (climate zones 3 and 12). This benefit cost ratio was calculated for the plenum heights of 3ft, 6ft, 9ft, 12ft and 15ft. This benefit cost ratio is the ratio of the energy cost savings benefits to incremental first cost of insulated roof and leaky ducts as compared to sealed ducts with lay-in insulation. The incremental costs are the initial costs of roof insulation (and in some conditions, insulation on plenum wall) minus the costs of lay-in insulation and duct sealing.

Table 21 (with ASHRAE values, CTZ3) indicates immediate cost benefits for only the insulated roof with uninsulated plenum wall for a specific height of 3 feet. For heights above 3 feet, this roof condition indicates negative energy savings and negative first costs, implying that for these conditions, lay-in insulation is more cost effective than insulation under roof deck.

Table 21: Benefit cost ratios of insulated roofs with leaky ducts (R4.2) versus insulated lay-in ceilings with tight ducts (R 8) using ASHRAE values, Climate zone 3

CTZ3 Benefit cost ratio-insul. roofs(leaky ducts) vs insul. Ceiling(tight ducts)-ASHRAE				
Plenum Hts	Insulated Plenum Wall		Uninsulated Plenum Wall	
	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.
3	(0.67)	(0.09)	Infinite *	0.28
6	(1.03)	(0.33)	14.06	(0.01)
9	(0.86)	(0.36)	30.58	(0.14)
12	(0.70)	(0.35)	41.62	(0.23)
15	(0.58)	(0.32)	49.58	(0.29)

(* Note: 'infinite' indicates immediate cost benefit. Numbers highlighted in white and in italics indicates negative energy costs and negative first costs)

Table 22 (with FSEC values, CTZ3) shows that the 'under deck insulation' with uninsulated plenum walls indicates immediate cost effectiveness for all plenum heights. The above deck insulated roof with uninsulated plenum and under deck insulated roof with insulated plenum wall indicates cost effectiveness for plenum height of 3 feet only.

Table 22: Benefit cost ratios of insulated roofs with leaky ducts (R4.2) versus insulated lay-in ceilings with tight ducts (R 8) using FSEC values, Climate zone 3

CTZ3 Benefit cost ratio-insul. roofs(leaky ducts) vs insul. Ceiling(tight ducts)-FSEC				
Plenum Hts	Insulated Plenum Wall		Uninsulated Plenum Wall	
	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.
3	2.83	0.67	Infinite *	1.25
6	0.37	0.17	Infinite *	0.78
9	(0.04)	0.01	Infinite *	0.56
12	(0.13)	(0.04)	Infinite *	0.43
15	(0.15)	(0.07)	Infinite *	0.33

(* Note: 'infinite' indicates immediate cost benefit)

Table 23 (with ASHRAE values, CTZ12) indicates cost effectiveness for all plenum heights and for all insulation conditions.

Table 23: Benefit cost ratio of insulated roofs with leaky ducts (R4.2) versus insulated lay-in ceiling with tight ducts (R 8) using ASHRAE values, Climate zone 12

CTZ12 Benefit cost ratio-insul. roofs(leaky ducts) vs insul. Ceiling(tight ducts)-ASHRAE				
	<i>Insulated Plenum Wall</i>		<i>Uninsulated Plenum Wall</i>	
Plenum Hts	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.
3	11.32	2.73	Infinite *	3.53
6	5.32	2.09	Infinite *	3.18
9	3.44	1.70	Infinite *	2.91
12	2.51	1.43	Infinite *	2.68
15	1.96	1.22	Infinite *	2.48

Table 24 (with FSEC values, CTZ12) indicates cost effectiveness for all plenum heights and for all insulation conditions.

Table 24: Benefit cost ratio of insulated roofs with leaky ducts (R4.2) versus insulated lay-in ceiling with tight ducts (R 8) using FSEC values, Climate zone 12

CTZ12 Benefit cost ratio-insul. roofs(leaky ducts) vs insul. Ceiling(tight ducts)-FSEC				
	<i>Insulated Plenum Wall</i>		<i>Uninsulated Plenum Wall</i>	
Plenum Hts	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.
3	15.81	3.78	Infinite *	4.92
6	7.84	3.06	Infinite *	4.75
9	5.26	2.58	Infinite *	4.63
12	3.97	2.23	Infinite *	4.50
15	3.17	1.96	Infinite *	4.38

Table 25 shows a summary of cost effectiveness of insulated roof decks versus insulated lay-in ceilings for climate zones 3, 6, 10, 12 and 14 based on which plenum heights show cost effectiveness. In the table below, 'None' represents no benefit costs for any of the plenum heights (3ft, 6ft, 9ft, 12ft and 15ft), 'All' represents cost effectiveness for all plenum heights, '<6', '<9', '<12' and '<15' represents cost effectiveness below 6 feet, 9 feet, 12 feet and 15 feet of plenum height.

This table is of interest because duct sealing is to be required for all roofs to be cost effective. The FSEC infiltration model has had larger documentation than that for ASHRAE and is based upon more recent studies¹⁵.

Table 25: Summary of Cost effectiveness of insulated roofs with leaky ducts versus, insulated lay-in ceilings with tight ducts (ASHRAE and FSEC values) for climate zones 3, 6, 10, 12 and 14

Summary-Cost effectiveness of insul. Roofs(leaky ducts) vs insul. lay-in ceiling(tight ducts)- ASHRA

Climate Zones	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.
CTZ3	None	None	<6	None
CTZ6	None	None	None	None
CTZ10	<6	None	<6	None
CTZ12	All	All	All	All
CTZ14	<6	None	<6	None

Summary-Cost effectiveness of insul. Roofs(leaky ducts) vs insul. lay-in ceiling(tight ducts)- FSEC

Climate Zones	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.
CTZ3	<6	None	All	<6
CTZ6	None	None	<6	<6
CTZ10	<12	<9	<15	<9
CTZ12	All	All	All	All
CTZ14	<15	<12	All	<12

3. Benefit cost ratios for insulated roof decks and drywall ceiling with tight ducts (R 8) versus insulated lay-in ceiling with tight ducts (R 8)

Table 26 and Table 27 show the benefit cost ratios for climate zones 3 and 12 of insulated roof decks and drywall ceilings with tight ducts (including R 8 duct insulation) versus insulated lay-in ceilings with tight ducts for the plenum heights of 3ft, 6ft, 9ft, 12ft and 15ft. This benefit cost ratio was calculated by taking the difference between the total TDV cost of lay-in insulation with the total TDV cost of roof deck and drywall ceiling insulation. This was then divided by the difference between the cost of insulation for roof decks and drywall ceilings with tight ducts and the cost of insulation for lay-in ceilings with tight ducts.

The results with ASHRAE values (Table 26) indicate cost effectiveness only for under deck roof insulation with uninsulated plenum with 3 feet height only.

¹⁵ See Cummings and Withers papers in reference section.

Table 26: Benefit cost ratios of insulated roofs and drywall ceilings with tight ducts (R 8) vs insulated lay-in ceilings with tight ducts (R 8) ASHRAE values, Climate zone 3

CTZ3						
Benefit cost ratio- insul. Roof/drywall (tight ducts) vs insul. Layin ceiling (tight duct)- ASHRAE						
Plenum Hts	Insulated Plenum Wall		Uninsulated Plenum Wall			
	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.	Drywall ceiling- UV	Drywall ceiling- V
3	0.13	0.08	1.35	0.43	(0.23)	0.04
6	(0.25)	(0.10)	0.91	0.30	(0.31)	(0.05)
9	(0.27)	(0.13)	0.81	0.27	(0.32)	(0.09)
12	(0.23)	(0.13)	0.78	0.26	(0.31)	(0.11)
15	(0.19)	(0.11)	0.79	0.26	(0.30)	(0.13)

Table 27 (CTZ3, with FSEC results) indicates that under deck insulated roof shows cost effectiveness for all plenum heights. Under deck insulated roof with insulated plenum and above deck insulated roof with uninsulated plenum indicate cost effectiveness for 3 feet plenum heights.

Table 27: Benefit cost ratios of insulated roofs and drywall ceilings with tight ducts (R 8) vs insulated lay-in ceilings with tight ducts (R 8) using FSEC values, Climate zone 3

CTZ3						
Benefit cost ratio- insul. Roof/drywall (tight ducts) vs insul. Layin ceiling (tight duct)- FSEC						
Plenum Hts	Insulated Plenum Wall		Uninsulated Plenum Wall			
	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.	Drywall ceiling- UV	Drywall ceiling- V
3	1.53	0.65	3.74	1.12	0.27	0.53
6	0.55	0.30	2.84	0.86	0.09	0.35
9	0.28	0.17	2.52	0.76	0.03	0.27
12	0.19	0.13	2.38	0.72	0.02	0.22
15	0.14	0.10	2.32	0.70	0.02	0.19

Table 28 (ASHRAE values) indicates a cost effectiveness for all insulated roofs except for both ventilated and unventilated drywall conditions.

Table 28: Benefit cost ratio of insulated roofs and drywall ceilings with tight ducts (R 8) vs insulated lay-in ceilings with tight ducts (R 8) using ASHRAE values, Climate zone 12

CTZ12 Benefit cost ratio- insul. Roof/drywall (tight ducts) vs insul. Layin ceiling (tight duct)- ASHRAE						
	<i>Insulated Plenum Wall</i>		<i>Uninsulated Plenum Wall</i>			
Plenum Hts	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.	Drywall ceiling- UV	Drywall ceiling- V
3	4.84	2.08	8.34	2.51	0.25	0.23
6	3.22	1.68	7.47	2.28	0.36	0.25
9	2.40	1.41	6.83	2.09	0.46	0.27
12	1.91	1.22	6.29	1.94	0.54	0.29
15	1.57	1.07	5.84	1.81	0.60	0.30

Table 29 (with FSEC values) indicates cost effectiveness for all insulated roofs for all plenum heights. The ventilated and unventilated drywall ceiling indicates cost effectiveness only for 3 feet plenum height.

Table 29: Benefit cost ratio of insulated roofs and drywall ceilings with tight ducts (R 8) vs insulated lay-in ceilings with tight ducts (R 8) using FSEC values, Climate zone 12

CTZ12 Benefit cost ratio- insul. Roof/drywall (tight ducts) vs insul. Layin ceiling (tight duct)- FSEC						
	<i>Insulated Plenum Wall</i>		<i>Uninsulated Plenum Wall</i>			
Plenum Hts	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.	Drywall ceiling- UV	Drywall ceiling- V
3	6.75	2.88	11.72	3.49	0.95	0.93
6	4.73	2.45	11.31	3.39	1.16	1.05
9	3.67	2.14	11.03	3.31	1.33	1.14
12	3.00	1.90	10.76	3.23	1.46	1.21
15	2.53	1.70	10.50	3.15	1.56	1.26

The results indicate that insulated drywall ceilings don't indicate cost effectiveness for any plenum heights for most climate zones. Insulating the ducts is cost effective in insulated roofs with uninsulated plenums. Marginal cost effectiveness is observed in roofs with insulated plenums.

Table 30 shows the summary of cost effectiveness of insulated roof decks and drywall ceilings with tight ducts versus insulated lay-in ceilings with tight ducts for climate zones 3, 6, 10, 12 and 14 based on which plenum heights show cost effectiveness. In the table below, 'None' represents no cost effectiveness for any of the plenum heights (3ft, 6ft, 9ft, 12ft and 15ft), 'All' represents cost effectiveness for all plenum heights, '<6'', '<9'', '<12'' and '<15'' represents cost effectiveness below 6 feet, 9 feet, 12 feet and 15 feet of plenum height.

The results indicate that insulated drywall ceilings don't indicate cost effectiveness for any plenum heights for most climate zones. Insulating the ducts is cost effective in insulated roofs with uninsulated plenums. Marginal cost effectiveness is observed in roofs with insulated plenums.

Table 30: Summary of Cost effectiveness of insulated roofs and drywall ceilings with tight ducts versus insulated lay-in ceilings with tight ducts (ASHRAE and FSEC) for climate zones 3, 6, 10, 12 and 14

Summary-Cost effectiveness of insul. roofs/drywall(tight ducts) vs insul. lay-in ceiling(tight ducts)- ASHRAE						
Climate Zones	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum-uninsul.	Drywall ceiling UV	Drywall ceiling V
CTZ3	None	None	<6	None	None	None
CTZ6	None	None	None	None	None	None
CTZ10	<6	None	<9	None	None	None
CTZ12	All	All	All	All	None	None
CTZ14	<6	None	<12	<6	None	None

Summary-Cost effectiveness of insul. roofs/drywall(tight ducts) vs insul. lay-in ceiling(tight ducts)- FSEC						
Climate Zones	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum-uninsul.	Drywall ceiling UV	Drywall ceiling V
CTZ3	<6	None	All	<6	None	None
CTZ6	None	None	<9	<6	None	None
CTZ10	<12	<9	All	All	None	<6
CTZ12	All	All	All	All	<6	<6
CTZ14	All	<12	All	All	<6	All

2. Mass building with pendant lighting

Description of Building Parametrics

Another set of DOE-2 simulations were carried out with slight modifications to the existing building model described in section "Building Simulation Models". The primary change was that all the heat (100%) heat from the luminaires was modeled to stay in the conditioned space. This is in contrast to the 'mass buildings with troffers' condition where 70% of heat from the luminaires ended up

in the conditioned space while 30% of the heat went to the plenum. In this new set of simulation runs, only the ventilated lay-in insulation conditions (ASHRAE and FSEC) were considered for analysis and the rest of the unventilated ceiling conditions were removed from the model. The parametric runs were performed for the following conditions:

- “Under deck plenum insul.” : insulated roof with **insulated** plenum walls and an uninsulated t-bar ceiling.
- “Under deck plenum uninsul.” : insulated roof with **uninsulated** plenum walls and an uninsulated t-bar ceiling.
- “Above deck plenum insul” : insulated roof with **insulated** plenum walls and an uninsulated t-bar ceiling.
- “Above deck plenum uninsul” : insulated roof with **uninsulated** plenum walls and an uninsulated t-bar ceiling.
- “Drywall-ventilated” : uninsulated roof deck and **uninsulated** plenum walls with an insulated drywall (low infiltration leakage area) ceiling with ventilated plenum.
- “Lay-in ASHRAE ventilated ” : uninsulated roof deck and **uninsulated** plenum walls with an average of 50-90% insulation coverage of the t-bar ceiling area. Air leakage through the ceiling uses the lower ASHRAE values.
- “Lay-in FSEC” : uninsulated roof deck and **uninsulated** plenum walls with an average of 50-90% insulation coverage of the t-bar ceiling area. Air leakage through the ceiling uses the higher FSEC values.

Two types of duct conditions were considered for this set of simulations- leaky duct with an R-value of 4.2 and tight duct with an R- value of 8. The percentage of leakage for a tight duct was considered as 8% and 36% for the leaky duct. The fraction of lighting power density to the conditioned space was taken as 100%.

The following sections deals with the results of cooling and heating loads and TDV savings for the two climate zones, 3 and 12, with leaky duct (R 4.2). The location of the insulation on the roof deck versus the ceiling showed the following results on the total cooling loads of the building are described below:

Analysis

The analysis of the simulation results was done based on the effect of insulation on cooling loads, heating loads, TDV savings and the benefit cost ratio of insulating.

Effects of Insulation Location on Cooling Loads

The total cooling loads (kBtu/sq ft) were plotted for the various insulation conditions that were simulated using the DOE-2 model. The results of two climate zones, 3 and 12, with leaky duct (R 4.2) situation are described below. The graphs of cooling and heating loads for tight ducts (R8) are shown in the Appendix B. It was observed that the cooling and heating loads of all insulating

conditions for tight ducts showed comparable patterns with the cooling and heating loads for the leaky ducts.

Climate Zone 3

- As the plenum height increases from 3 feet to 15 feet, there is a decrease in the total cooling loads for all the various insulation conditions. As the plenum height increases, there is greater thermal mass available and greater heat transfer to the mild ambient conditions.
- The cooling loads of insulated roof decks with uninsulated plenum wall have the lowest cooling loads. Cooling loads for roof decks with insulated plenums have higher values. The reason is possibly that plenum walls that are not insulated help in more heat loss than when plenum walls are insulated (which prevents heat loss).
- The dry-wall insulation condition has the highest cooling loads because the ducts being leaky, result in loss of a significant amount of cooling energy. The insulated drywall ceiling has the least opportunity for 'regain' (that is, there is a barrier to heat flow between the plenum in conditioned space).
- The insulated roof deflects solar loads. The uninsulated mass wall condition provides a shift of cooling loads to the after operation hours of HVAC system. The relatively low thermal resistance to outdoors allows the rejection of heat load during mild weather.
- The lay-in insulation with FSEC results indicates lower cooling load values than drywall or ASHRAE lay-in condition. This could be attributed to higher infiltration rates with a mild climate zone. Since the HVAC does not have an economizer, the building is rejecting heat for a significant number of hours.

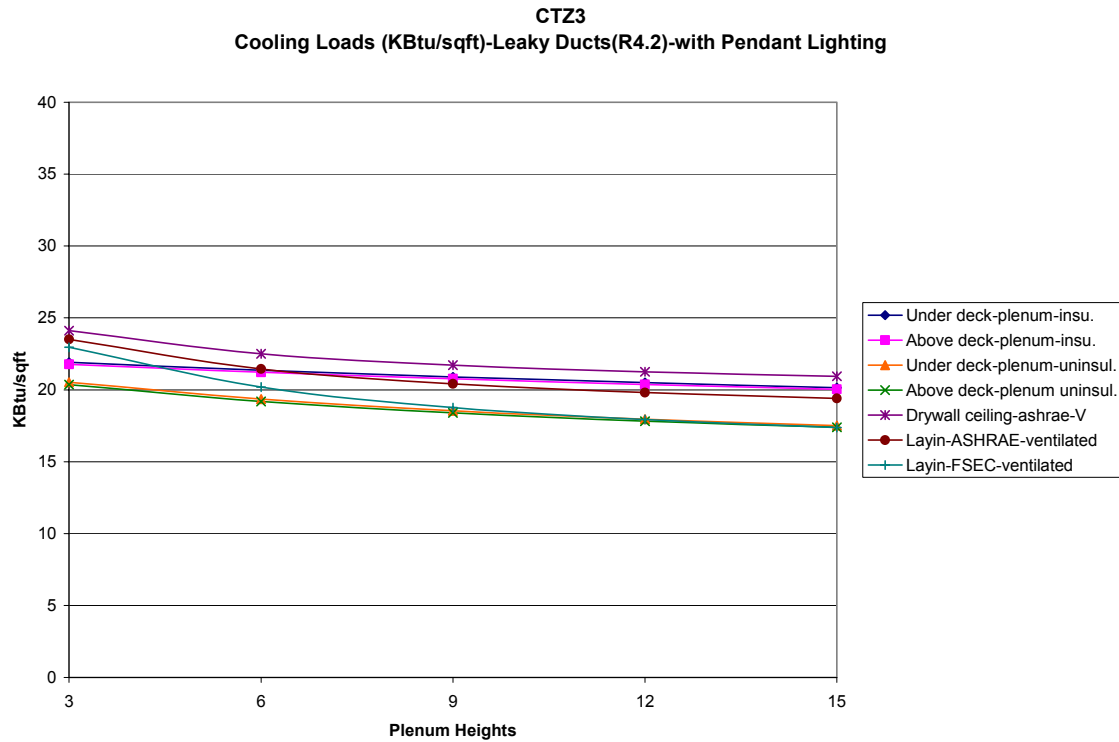


Figure 21: Cooling loads with varying plenum heights- Climate Zone 3

Climate Zone 12

- The cooling loads for CTZ 12 decrease to a small amount with increase in plenum heights.
- Insulated roofs with two different conditions (plenum walls insulated and uninsulated) have lower cooling loads than insulated ceilings. This is attributed to the fact that when insulation is placed on the roof, the heat transfer to plenum is minimal. When insulation is on the ceiling, there is more heat transfer to the plenum from outdoors and hence more heat transfer to conditioned space.
- All the insulated ceilings (drywall ceiling, lay-in with ASHRAE and FSEC infiltration) have similar patterns of cooling loads.

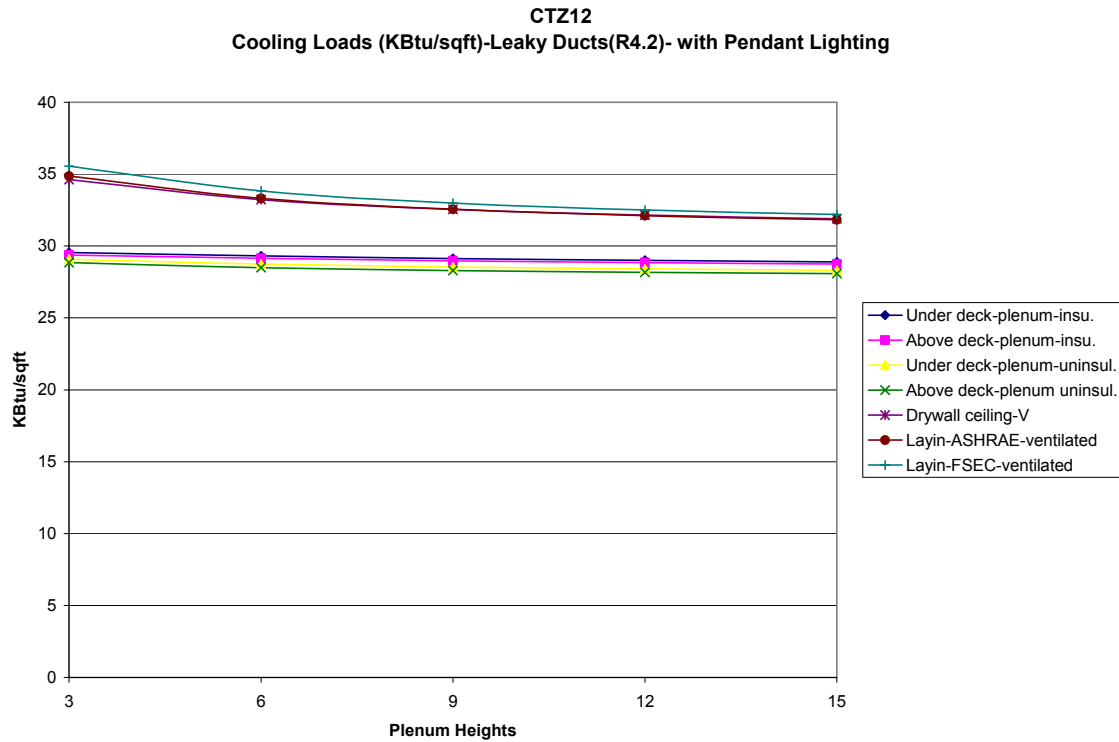


Figure 22: Cooling loads with varying plenum heights- Climate Zone 12

Effects of Insulation Location on Heating Loads

Climate Zone 3

- Heating loads increase with increase in plenum height for all insulation conditions. With increase in plenum height, the volume of plenum space also increases, which results in higher infiltration in the plenum and high conductance to the plenum and hence the need for more heating.
- Insulated roofs with uninsulated plenum walls have higher heating loads than when plenum walls are insulated. This is due to higher conduction losses.
- Both the insulated roofs and insulated drywall ceilings have lower heating loads than lay-in insulated ceiling because high infiltration rates through the lay-in ceiling by-passed the thermal resistance of the insulation.
- Among insulated ceilings, lay-in insulated ceiling with FSEC values has the highest heating loads. This can be attributed to the fact that this insulated ceiling condition has higher infiltration rate.

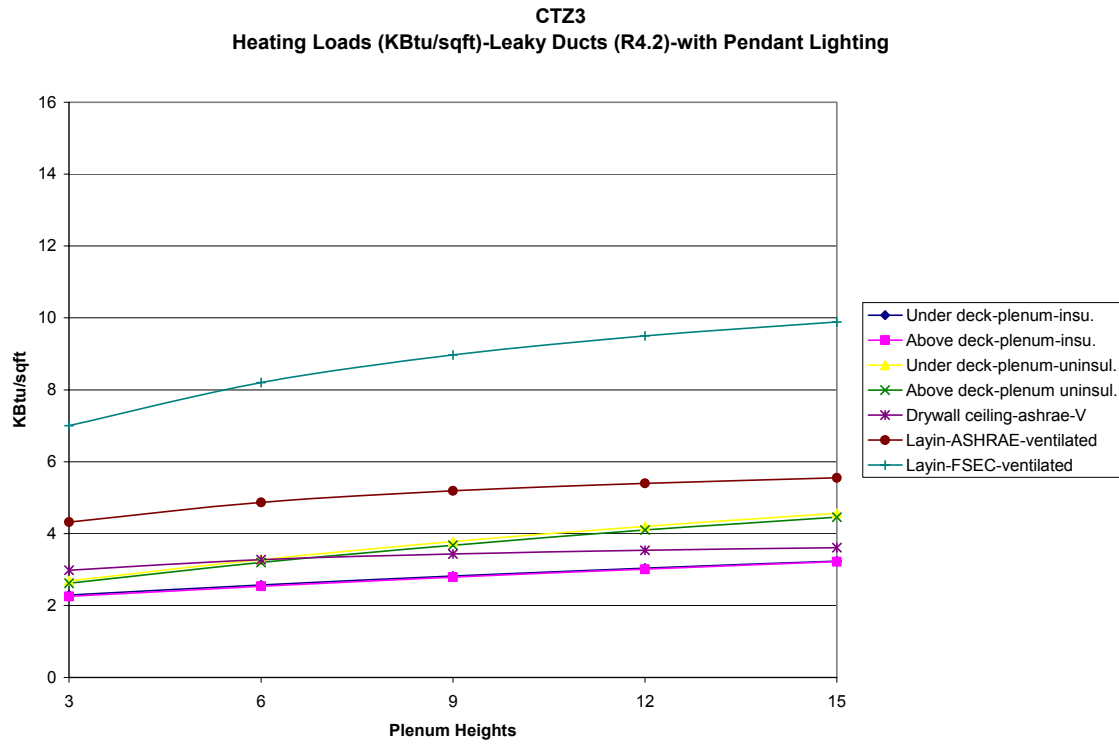


Figure 23: Heating loads with varying plenum heights-Climate Zone 3

Climate Zone 12

- The heating loads for this climate zone are mostly similar to the case in climate zone 3, except that the magnitude of the loads are higher in the more extreme climate like climate zone 12.

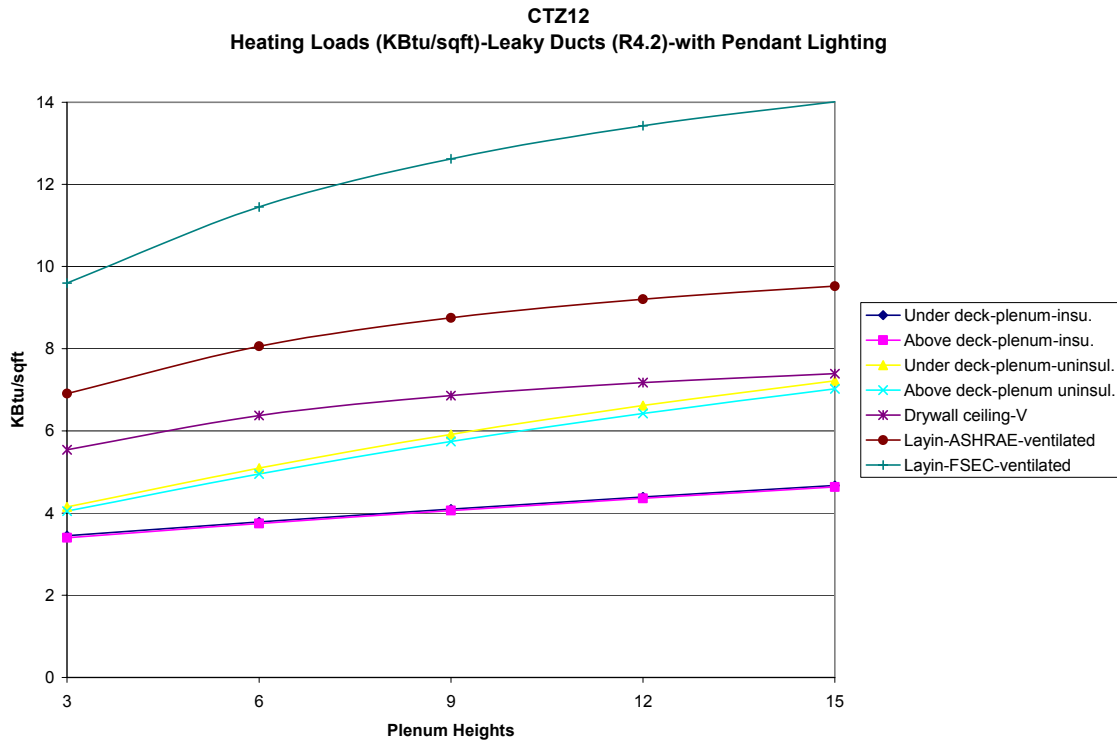


Figure 24: Heating loads with varying plenum heights-Climate Zone-12

Effects of Insulation Position on TDV Savings

The TDV savings for insulated roof decks and drywall ceiling were analyzed based on the lay-in insulated acoustic tile ceilings using both the ASHRAE and FSEC values of ventilation rates. The TDV savings for climate zone 3 and 12 with leaky ducts is described below:

Climate Zone 3

- TDV savings decrease with increase in plenum heights. This is attributed to the decrease in cooling loads with increasing plenum heights.
- TDV savings for insulated roof decks with uninsulated plenum walls have more TDV savings than insulated roof decks with insulated plenum walls. This can be attributed the thermal mass benefits of uninsulated plenum walls.
- Insulated drywall ceiling indicate minimum TDV savings. This is primarily due to an increase in cooling loads due to insulation from the thermal mass effects in the plenum and minimal regain of duct losses.
- FSEC values indicate more TDV savings for all insulation conditions when compared to ASHRAE values. Though TDV preferentially weighs the value of cooling loads, there is a substantially greater effect on heating loads than on cooling loads.

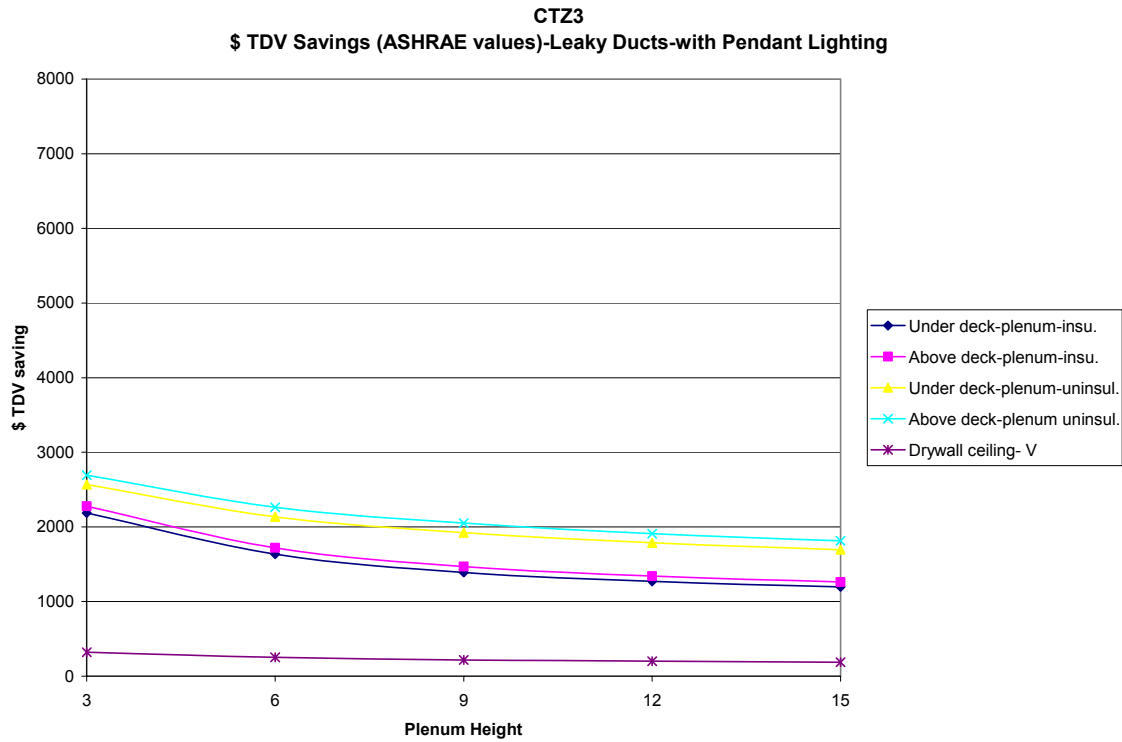


Figure 25: TDV savings with varying plenum heights (ASHRAE values)-Climate zone 3

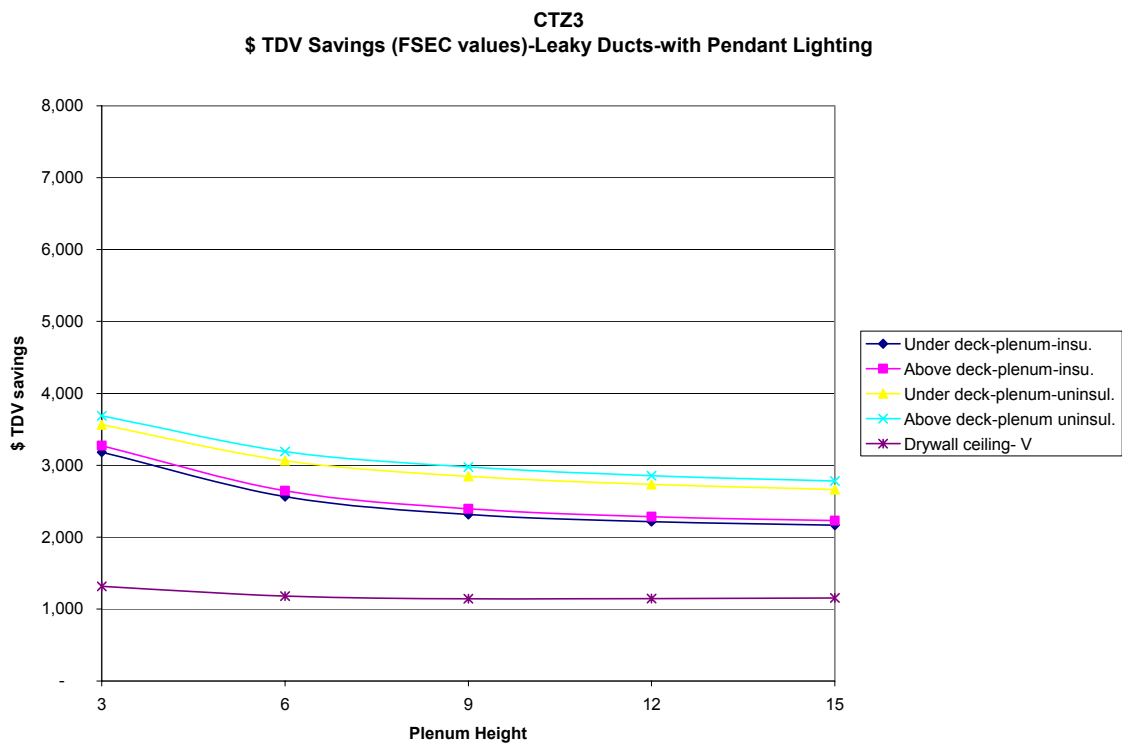


Figure 26: TDV savings with varying plenum heights (FSEC values)-Climate Zone 3

Climate Zone 12

- ASHRAE values: TDV savings for all insulated roof deck conditions decrease with increase in plenum heights. But insulated drywall ceiling shows a slight increase in TDV savings with increasing plenum height. This is because the increase in heating loads for the drywall ceiling is increased at a slightly slower rate than that of the lay-in insulated suspended ceiling.
- FSEC values: TDV savings for insulated roof-decks with uninsulated plenum decrease with increasing plenum heights. However, it is the other way around for roof decks with insulated plenum walls where TDV savings increase slightly with increasing plenum heights.

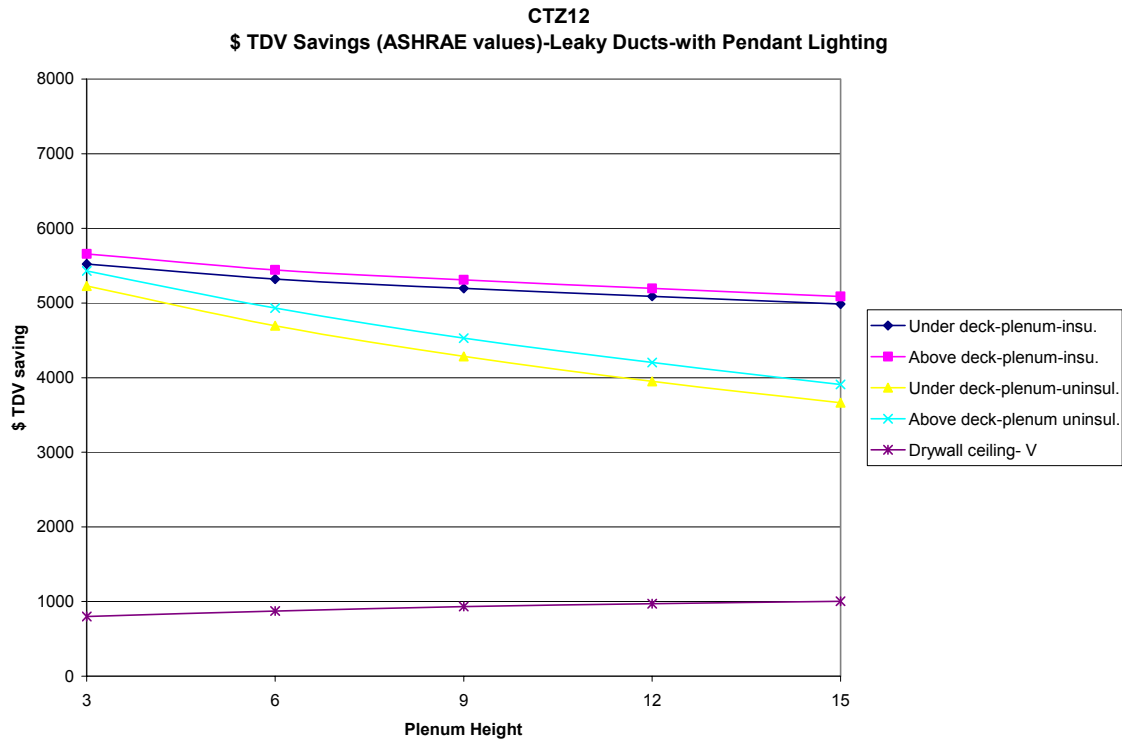


Figure 27: TDV savings with varying plenum heights (ASHRAE values)-Climate Zone 12

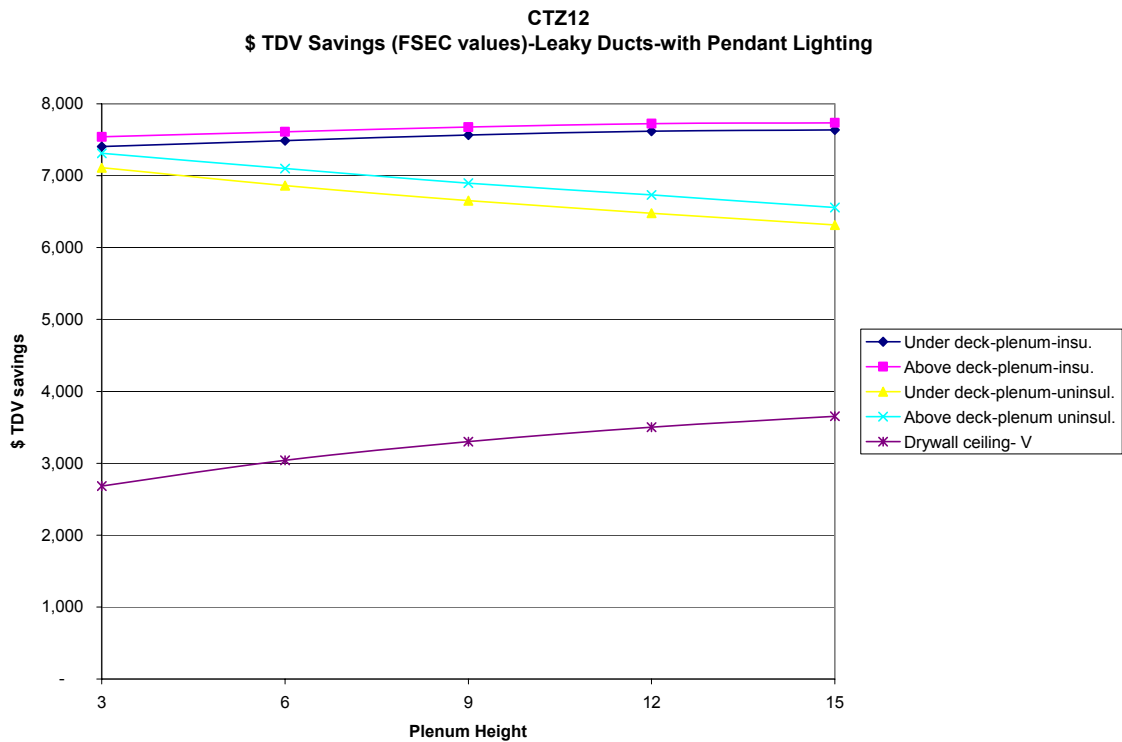


Figure 28: TDV savings with varying plenum heights (FSEC values)-Climate Zone 12

Benefit Cost Ratio

The benefit cost analysis was done based on the TDV savings and the difference in the material costs of all the roofing insulation options as compared to lay-in insulation costs. The following tables show the benefit cost ratios for climate zone 3 and 12, along with a summary of benefit cost ratio of all the five climate zones under study. The benefit cost ratios for climate zones 6, 10 and 14 are in Appendix B.

1. Benefit cost ratios of sealing and insulating ducts for insulated roofs, drywall and lay-in ceilings

Table 31 shows the benefit cost ratios for tightening the ducts and adding duct insulation (from R 4.2 to R 8) for insulated roof decks, drywall and lay-in ceiling conditions for climate zone 3. The benefit cost ratios were calculated for the plenum heights of 3ft, 6ft, 9ft, 12ft and 15ft. The calculation method is described in the “1. Mass Building with Troffers” section.

The insulated drywall and lay-in ceilings show cost effectiveness for all plenum heights. Among the insulated roof decks, the ones with insulated plenum walls show cost effectiveness for plenum heights greater than 12'. The roof decks with uninsulated plenum wall show cost effectiveness for all plenum heights except at 3 feet height.

Table 31: Benefit cost ratio of sealing ducts and increasing duct insulation from R 4.2 to R 8 - Climate Zone 3

CTZ3							
Benefit cost ratio for tightening ducts for all insulation conditions							
	Insulated Plenum Wall		Uninsulated Plenum Wall				
Plenum Hts	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.	Drywall ceiling V	Lay-in-V-ASHRAE	Lay-in-V-FSEC
3	0.67	0.63	0.90	0.81	3.62	3.51	3.07
6	0.80	0.76	1.14	1.04	3.40	3.58	3.52
9	0.94	0.90	1.34	1.24	3.27	3.57	3.77
12	1.04	1.00	1.51	1.40	3.18	3.57	3.93
15	1.13	1.10	1.63	1.53	3.13	3.57	4.06

Table 32 shows the benefit cost ratios for tightening the ducts and adding duct insulation (from R 4.2 to R 8) for insulated roof decks, drywall and lay-in ceiling conditions for climate zone 12. The under deck and above deck insulated roof with plenum insulated showed a benefit cost only for specific heights (above 3 feet for under deck and above 6' for above deck). The rest of the insulation conditions showed cost effectiveness for all plenum heights.

Table 32: Benefit cost ratio of sealing ducts and increasing duct insulation from R 4.2 to R 8 - Climate Zone 12

CTZ12							
Benefit cost ratio for Tightening Ducts for all insulation conditions							
	Insulated Plenum Wall		Uninsulated Plenum Wall				
Plenum Hts	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum-uninsul.	Drywall ceiling- V	Lay-in-V-ASHRAE	Lay-in-V-FSEC
3	0.86	0.79	1.30	1.15	7.34	6.83	5.59
6	1.04	0.97	1.89	1.68	7.92	7.85	7.24
9	1.23	1.17	2.46	2.23	8.23	8.41	8.21
12	1.42	1.35	2.95	2.68	8.43	8.76	8.86
15	1.56	1.50	3.38	3.11	8.57	9.01	9.33

Table 33 shows a summary of benefit cost ratios for tightening the ducts for roof decks and drywall ceiling for all climate zones based on which plenum heights show cost effectiveness. In this table, 'All' represents cost effectiveness for all plenum heights, >3', >6' and >9' represents cost effectiveness above 3 feet, 6 feet and 9 feet of plenum height.

Tightening of ducts was mostly cost effective for all insulation conditions for all plenum heights in most climate zones. This pattern is due to the high 'regaining' of the plenum that have insulated roofs and side walls. The cooling or heating that is lost from ducts is not lost to the outside but is "regained" or replaced loads on to the conditioned space. Thus sealing and insulating plenums does not save much energy since the plenum is essentially in conditioned space.

Table 33: Summary of cost effectiveness of tightening ducts for insulated roofs, and drywall and lay-in ceilings for climate zones 3, 6, 10, 12 and 14

Summary-Cost effectiveness of tightening ducts							
Climate Zones	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum-uninsul.	Drywall ceiling V	Lay-in-V-ASHRAE	Lay-in-V-FSEC
CTZ3	>9	>9	>3	>3	All	All	All
CTZ6	>3	>3	All	All	All	All	All
CTZ10	>3	>3	All	All	All	All	All
CTZ12	>3	>6	All	All	All	All	All
CTZ14	All	>3	All	All	All	All	All

2. Benefit cost ratio of insulated roof decks with leaky ducts (R 4.2) versus insulated lay-in ceiling with tight ducts (R 8)-Climate zone 3

The second case determines the benefit cost ratios of insulated roof deck conditions with leaky ducts (R 4.2) versus insulated lay-in ceilings with tight ducts

(R 8) for both ASHRAE and FSEC values. This benefit cost ratio is calculated for the plenum heights of 3ft, 6ft, 9ft, 12ft and 15ft.

Table 34 (ASHRAE values) shows that in climate zone 3, the 'under deck insulated roof with uninsulated plenum wall' is cost effective (has immediate pay back) for plenum heights 3' and 6'. For heights above 6', this condition results in negative costs and negative TDV savings. Remaining three conditions (under and above deck insulated and above deck uninsulated) show no cost effectiveness for any plenum heights.

Table 34: Benefit cost ratios of insulated roofs with leaky ducts (R4.2) versus insulated lay-in ceilings with tight ducts (R 8) using ASHRAE values -Climate zone 3

CTZ3				
Benefit cost ratio-insul. roofs(leaky ducts) vs insul. Ceiling(tight ducts)-ASHRAE				
	Insulated Plenum Wall		Uninsulated Plenum Wall	
Plenum Hts	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.
3	0.17	0.09	Infinite *	0.40
6	(0.61)	(0.18)	Infinite *	0.09
9	(0.59)	(0.24)	17.63	(0.05)
12	(0.51)	(0.25)	28.91	(0.14)
15	(0.44)	(0.24)	36.74	(0.20)

(Note: infinite* indicates immediate cost benefit. Numbers highlighted in white and in italics indicates negative energy costs and negative first costs)

Table 35 (FSEC values) indicates an immediate cost benefit for under deck insulated roof with uninsulated plenum walls for all plenum heights. The rest of the conditions show cost benefit only for plenum heights of 3 feet.

Table 35: Benefit cost ratios of insulated roofs with leaky ducts (R4.2) versus insulated lay-in ceilings with tight ducts (R 8) using FSEC values -Climate zone 3

Benefit cost ratio-insul. roofs(leaky ducts) vs insul. Ceiling(tight ducts)-FSEC				
	Insulated Plenum Wall		Uninsulated Plenum Wall	
Plenum Hts	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.
3	3.23	0.75	Infinite *	1.26
6	0.52	0.23	Infinite *	0.73
9	0.04	0.05	Infinite *	0.49
12	(0.09)	(0.03)	Infinite *	0.34
15	(0.13)	(0.06)	Infinite *	0.24

(Note: infinite* indicates immediate cost benefit)

Table 36 indicates that for climate zone 12 with ASHRAE values, the under deck insulated roof (both with insulated and uninsulated plenum wall) has a cost

effectiveness for plenum height of 3 feet. The above deck insulated roof (both with insulated and uninsulated plenum wall) indicate no cost effectiveness for any plenum heights.

Table 36: Benefit cost ratio of insulated roofs with leaky ducts (R4.2) versus insulated lay-in ceiling with tight ducts (R 8) using ASHRAE values -Climate zone 12

CTZ12 Benefit cost ratio-insul. roofs(leaky ducts) vs insul. Ceiling(tight ducts)-ASHRAE				
	<i>Insulated Plenum Wall</i>		<i>Uninsulated Plenum Wall</i>	
Plenum Hts	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.
3	3.09	0.80	Infinite *	0.89
6	0.66	0.31	2.92	0.14
9	0.12	0.10	68.56	(0.35)
12	(0.08)	(0.01)	116.66	(0.72)
15	(0.17)	(0.08)	155.10	(1.01)

(* Note: 'infinite' indicates immediate cost benefit. Numbers highlighted in white and in italics indicates negative energy costs and negative first costs)

Table 37 indicates that for climate zone 12 with FSEC values, insulated roof decks with insulated plenum walls show cost effectiveness for certain plenum heights (less than 15' for under deck and less than 9' for above deck). Insulated under roof-deck with uninsulated plenum wall show immediate cost benefits for all plenum heights while above deck insulated roof indicates cost effectiveness for height below 12'.

Table 37: Benefit cost ratio of insulated roofs with leaky ducts (R4.2) versus insulated lay-in ceiling with tight ducts (R 8) using FSEC values -Climate zone 12

CTZ12 Benefit cost ratio-insul. roofs(leaky ducts) vs insul. Ceiling(tight ducts)-FSEC				
	<i>Insulated Plenum Wall</i>		<i>Uninsulated Plenum Wall</i>	
Plenum Hts	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.
3	8.95	2.17	Infinite *	2.69
6	3.43	1.36	Infinite *	1.87
9	1.92	0.97	Infinite *	1.34
12	1.26	0.73	Infinite *	0.96
15	0.89	0.57	Infinite *	0.65

Table 38 shows the summary of cost effectiveness for insulated roof decks versus insulation lay-in ceilings for climate zones 3, 6, 10, 12 and 14 based on which plenum heights show cost effectiveness. In the table below, 'None'

represents no cost effectiveness for any of the plenum heights (3ft, 6ft, 9ft, 12ft and 15ft), 'All' represents cost effectiveness for all plenum heights, <6', <9', <12' and <15' represents cost effectiveness below 6 feet, 9 feet, 12 feet and 15 feet of plenum height. Here, under deck insulated roof with uninsulated plenum wall indicates cost effectiveness for all plenum heights in most climate zones (with FSEC values).

Table 38: Summary of Cost effectiveness of insulated roofs with leaky ducts versus, insulated lay-in ceilings with tight ducts (ASHRAE and FSEC values) for climate zones 3, 6, 10, 12 and 14

Summary-Cost effectiveness of insul. Roofs(leaky ducts) vs insul. lay-in ceiling(tight ducts)- ASHRAE

Climate Zones	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.
CTZ3	None	None	<9	None
CTZ6	None	None	None	None
CTZ10	<6	None	<6	<3
CTZ12	<6	None	<6	None
CTZ14	<6	<6	<6	<6

Summary-Cost effectiveness of insul. Roofs(leaky ducts) vs insul. lay-in ceiling(tight ducts)- FSEC

Climate Zones	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.
CTZ3	<6	None	All	<6
CTZ6	<6	None	<6	<6
CTZ10	<12	<9	<15	<9
CTZ12	<15	<9	All	<12
CTZ14	<15	<12	All	<12

As described in the earlier section of “1. Mass Building with Troffers”, the FSEC infiltration model is given more credence. Insulation under roof deck is a cost effective alternative to lay-in insulation for most plenum heights when the plenum heights are uninsulated in all climate zones and in the most extreme climate zones when the plenum walls are insulated. This comparison of sealed ducts are compared to unsealed ducts under insulated roofs is important because this is a cost-effective solution for duct sealing.

3. Benefit cost ratio for Insulated roof decks and drywall ceiling with tight ducts (R 8) versus insulated lay-in ceiling with tight ducts (R 8)

The following tables show the benefit cost ratios for climate zones 3 and 12 for insulated roof decks and drywall ceilings with tight ducts (R 8) versus insulated lay-in ceilings with tight ducts for the plenum heights of 3ft, 6ft, 9ft, 12ft and 15ft.

Table 39 (ASHRAE results-climate zone 3) indicates that the under deck insulated roof with uninsulated plenum walls is cost effective for plenum heights

less than 12' while the rest of the four conditions show no cost effectiveness for any plenum heights.

Table 39: Benefit cost ratio of insulated roofs/drywall ceiling with tight ducts (R 8) versus insulated lay-in ceiling with tight ducts (R 8) using ASHRAE values for plenum heights of 3ft, 6ft, 9ft, 12ft and 15ft- Climate zone 3

CTZ3					
Benefit cost ratio- insul. Roof/drywall (tight ducts) vs insul. Layin ceiling (tight duct)- ASHRAE					
	Insulated Plenum Wall		Uninsulated Plenum Wall		
Plenum Hts	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.	Drywall ceiling
3	0.47	0.22	1.68	0.52	0.13
6	(0.01)	0.02	1.17	0.37	0.06
9	(0.09)	(0.03)	1.04	0.33	0.02
12	(0.09)	(0.04)	0.99	0.32	0.00
15	(0.08)	(0.04)	0.98	0.31	(0.01)

Table 40 (FSEC results-climate zone 3) shows cost effectiveness as follows:

Under deck plenum uninsulated (all plenum heights), under deck plenum insulated (below 6 feet plenum height), above deck plenum uninsulated (below 6 feet height), no cost effectiveness for any plenum heights for insulation above roof-deck and insulated drywall ceiling. The difference between tables 37 and 38 is that the FSEC model includes greater infiltration rates in lay-in ceilings.

Table 40: Benefit cost ratio of insulated roofs/drywall ceiling with tight ducts (R 8) versus insulated lay-in ceiling with tight ducts (R 8) using FSEC values for plenum heights of 3ft, 6ft, 9ft, 12ft and 15ft- Climate zone 3

CTZ3					
Benefit cost ratio- insul. Roof/drywall (tight ducts) vs insul. Layin ceiling (tight duct)- FSEC					
	Insulated Plenum Wall		Uninsulated Plenum Wall		
Plenum Hts	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.	Drywall ceiling
3	1.70	0.72	3.78	1.13	0.57
6	0.64	0.34	2.74	0.82	0.38
9	0.33	0.20	2.35	0.71	0.29
12	0.21	0.14	2.16	0.65	0.24
15	0.15	0.11	2.05	0.62	0.21

Table 41 and Table 42 indicate the benefit cost ratio for both ASHRAE and FSEC results for climate zone 12. The FSEC results show more cost effectiveness for all insulation conditions when compared to the ASHRAE results.

Table 41: Benefit cost ratio of insulated roofs and drywall ceilings with tight ducts (R 8) versus insulated lay-in ceilings with tight ducts (R 8) using ASHRAE values- Climate zone 12

Benefit cost ratio- insul. Roof/drywall (tight ducts) vs insul. Layin ceiling (tight duct)- ASHRAE					
	Insulated Plenum Wall		Uninsulated Plenum Wall		
Plenum Hts	Metal roof-plenum-insu.	Rigid roof-plenum-insu.	Metal roof-plenum-uninsul.	Rigid roof-plenum uninsul.	Drywall ceiling- V
3	1.81	0.79	3.16	0.96	0.37
6	0.81	0.44	1.88	0.59	0.32
9	0.46	0.29	1.23	0.41	0.29
12	0.29	0.20	0.83	0.28	0.28
15	0.19	0.14	0.55	0.20	0.27

Table 42: Benefit cost ratio of insulated roofs and drywall ceilings with tight ducts (R 8) vs insulated lay-in ceilings with tight ducts (R 8) using FSEC values - Climate zone 12

CTZ12 Benefit cost ratio- insul. Roof/drywall (tight ducts) vs insul. Layin ceiling (tight duct)- FSEC					
	Insulated Plenum Wall		Uninsulated Plenum Wall		
Plenum Hts	Metal roof-plenum-insu.	Rigid roof-plenum-insu.	Metal roof-plenum-uninsul.	Rigid roof-plenum uninsul.	Drywall ceiling- V
3	4.30	1.84	7.57	2.24	1.28
6	2.47	1.28	6.10	1.81	1.19
9	1.71	1.00	5.38	1.60	1.15
12	1.30	0.83	4.93	1.47	1.13
15	1.03	0.70	4.62	1.37	1.12

Table 43 shows a summary of cost effectiveness of insulated roof decks and drywall ceilings with tight ducts versus insulated lay-in ceilings with tight ducts for climate zones 3, 6, 10, 12 and 14 based on which plenum heights show cost effectiveness. In the table below, 'None' represents no cost effectiveness for any of the plenum heights (3ft, 6ft, 9ft, 12ft and 15ft), 'All' represents cost effectiveness for all plenum heights, '<6'', '<9'', '<12'' and '<15'' represents cost effectiveness below 6 feet, 9 feet, 12 feet and 15 feet of plenum height. In this case, insulated roof decks with uninsulated plenum indicate cost effectiveness for all plenum heights for most climate zones (with FSEC values).

Table 43: Summary of Cost effectiveness of insulated roofs and drywall ceilings with tight ducts versus insulated lay-in ceilings with tight ducts (ASHRAE and FSEC values) for climate zones 3, 6, 10, 12 and 14

Summary-Cost effectiveness of insul. roofs/drywall(tight ducts) vs insul. lay-in ceiling(tight ducts)- ASHRAE					
Climate Zones	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.	Drywall ceiling- V
CTZ3	None	None	<12	None	None
CTZ6	None	None	<6	None	None
CTZ10	<6	None	<12	<6	None
CTZ12	<6	None	<12	None	None
CTZ14	<6	<6	<12	<6	None

Summary-Cost effectiveness of insul. roofs/drywall(tight ducts) vs insul. lay-in ceiling(tight ducts)- FSEC					
Climate Zones	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.	Drywall ceiling- V
CTZ3	<6	None	All	<6	None
CTZ6	<6	None	<9	<6	None
CTZ10	<15	<9	All	All	<12
CTZ12	All	<12	All	All	All
CTZ14	All	<12	All	All	All

3. Wood Frame Wall With Pendant Lighting

Description of Building Parametrics

This analysis was based on a wood frame wall building with pendant lighting. All conditions of the building were identical to the case 2- “mass wall with pendant lighting” (refer to section “2. Mass building with pendant lighting” for building parameters). Some of the changed parameters in this case study were: was the

- Wall construction of the plenum walls was made of wood frame with the following components: ½ inch plywood board, fiber glass batt insulation (R11 or R13 depending on climate zones) and stucco.
- Here, there were on conditions with “uninsulated plenum walls since this is not allowed by the Title 24 for light weight thermal mass or frame wall construction.

Analysis

This section deals with the results of cooling and heating loads and TDV savings for the two climate zones, 3 and 12, with leaky duct (R 4.2). The location of the insulation on the roof deck versus the ceiling showed the following results on the total cooling loads of the building are described below:

Effects of Insulation Location on Cooling Loads***Climate Zone 3***

- The increase in plenum height results in slight decrease in cooling loads for all insulated ceiling conditions. This could be attributed to the increased CFM in the ceiling when the temperatures are mild.
- Cooling loads of insulated drywall ceiling was higher than lay-in insulated ceilings. This is likely due to lower regain of duct losses through the insulated drywall ceiling.

Climate Zone 12

- In climate zone 12, the outside air conditions result in higher cooling loads for lay-in insulation than the drywall ceiling. Under no plenum heights does the lay-in insulation have lower cooling loads than insulated roofs.
- Insulated roof decks indicate a slight increase in cooling loads with increase in plenum heights.

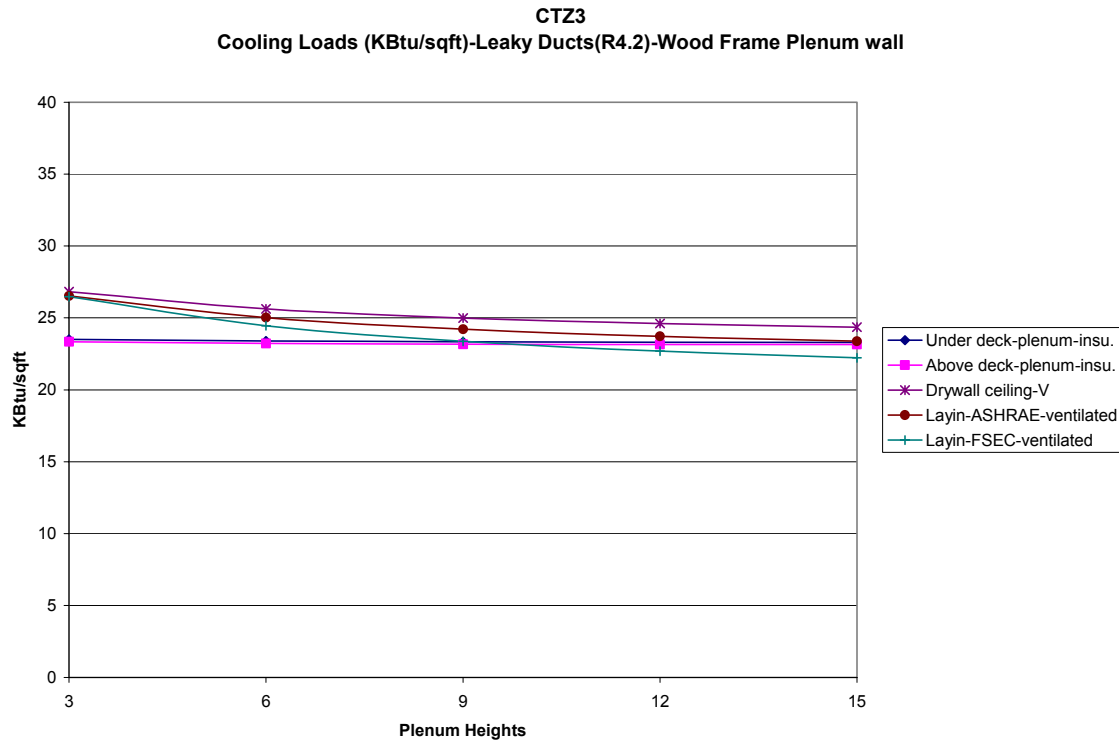


Figure 29: Cooling loads with varying plenum heights-Climate zone 3

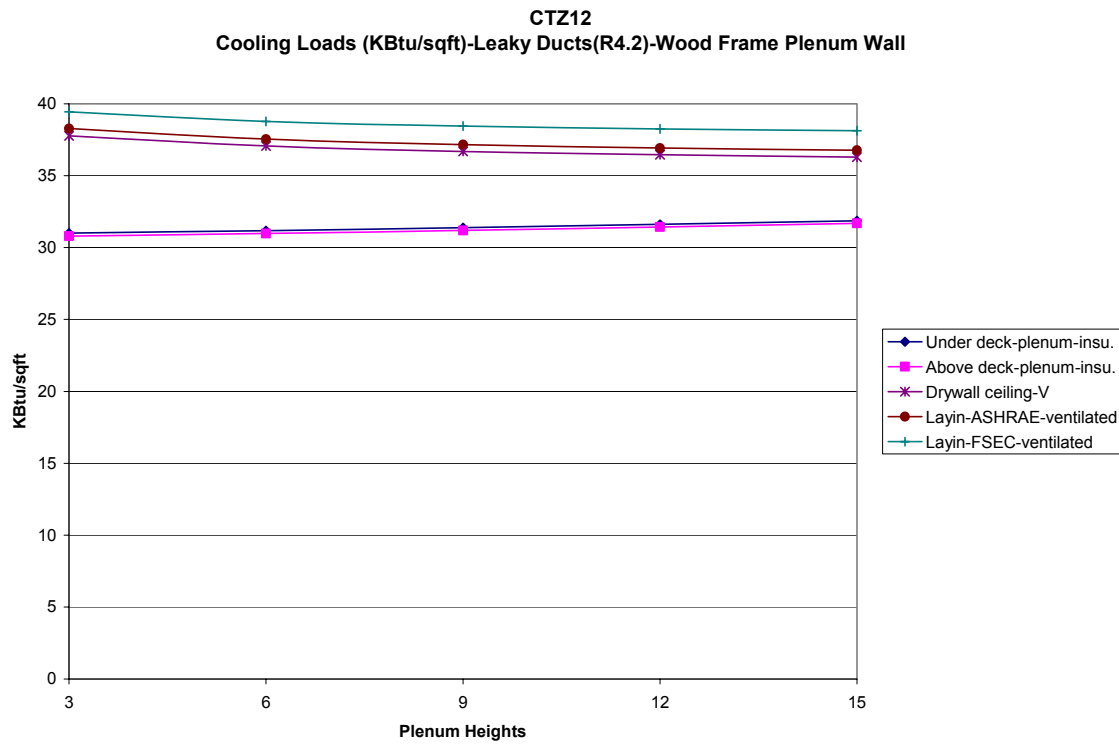


Figure 30: Cooling loads with varying plenum heights-Climate zone 12

Effects of Insulation Location on Heating Loads

Climate Zone 3

- The heating loads increase with increase in plenum heights. This is due to the increase in volume of plenum space and higher CFM that results in more heating loads in the conditioned space.
- The Lay-in ceiling (FSEC) was observed to have the maximum heating loads, which can be attributed to higher infiltration rates for this condition.

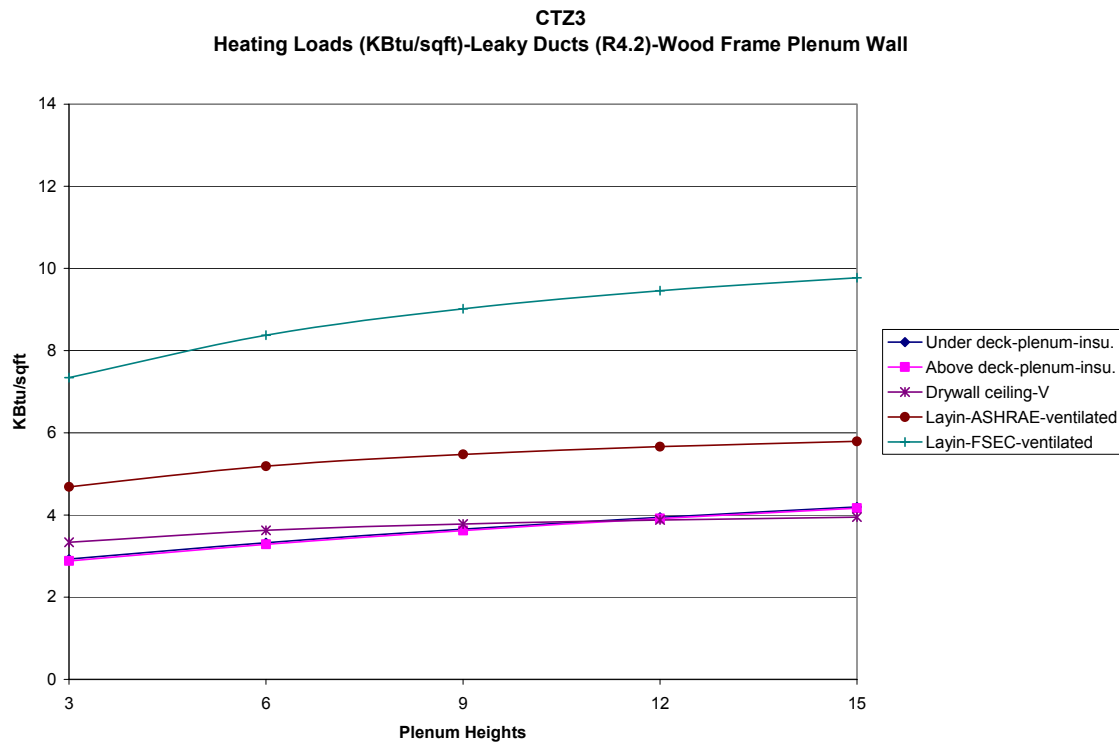


Figure 31: Heating loads with varying plenum heights- Climate zone 3

Climate Zone 12

The results of this climate zone were quite similar in performance of insulated roofs/ceilings except in case of the drywall, it showed a higher value than the roof decks with insulated plenum wall.

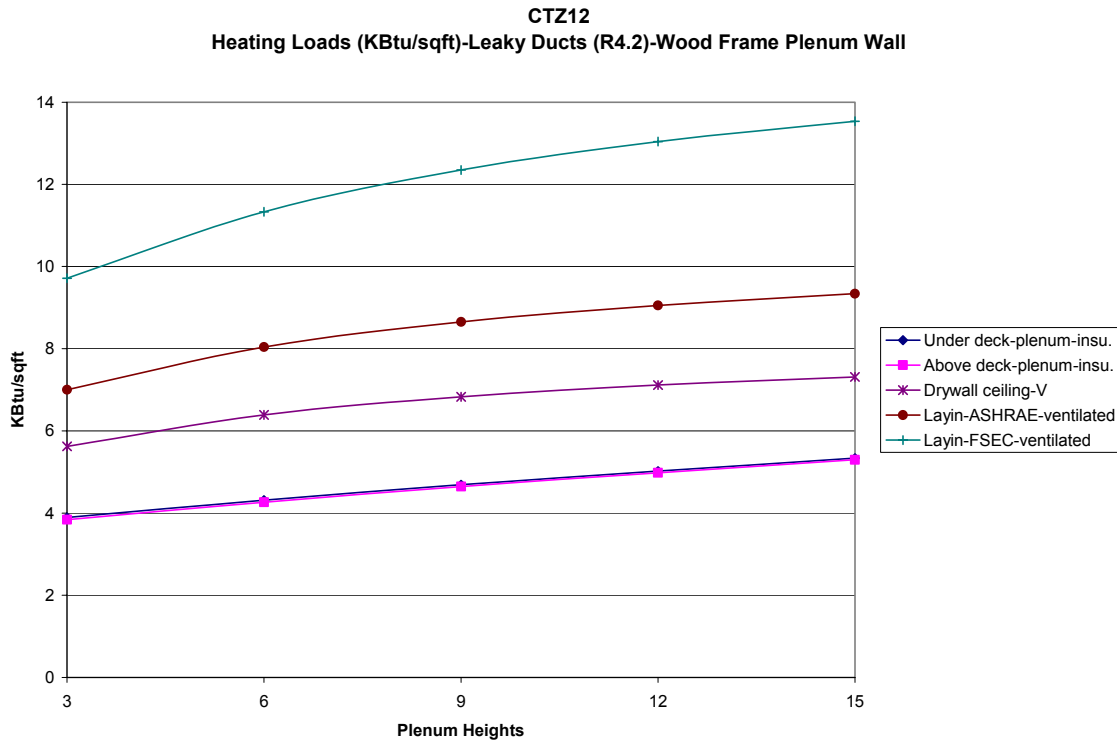


Figure 32: Heating loads with varying plenum heights- Climate zone 12

Effects of Insulation Position on TDV Savings

Climate Zone 3

- Both ASHRAE and FSEC values showed similar patterns of TDV savings in all insulation conditions. TDV savings decrease with increase in plenum heights and this is due to the cooling loads decreasing with increase in plenum heights.
- FSEC TDV savings are higher than ASHRAE TDV savings

Climate Zone 12

- Climate zone 12 showed similar results with the climate zone 3 (both ASHRAE and FSEC conditions).
- More savings observed in CTZ 12 when compares to CTZ 3. This is because cooling loads of CTZ 12 are much higher than CTZ 3.

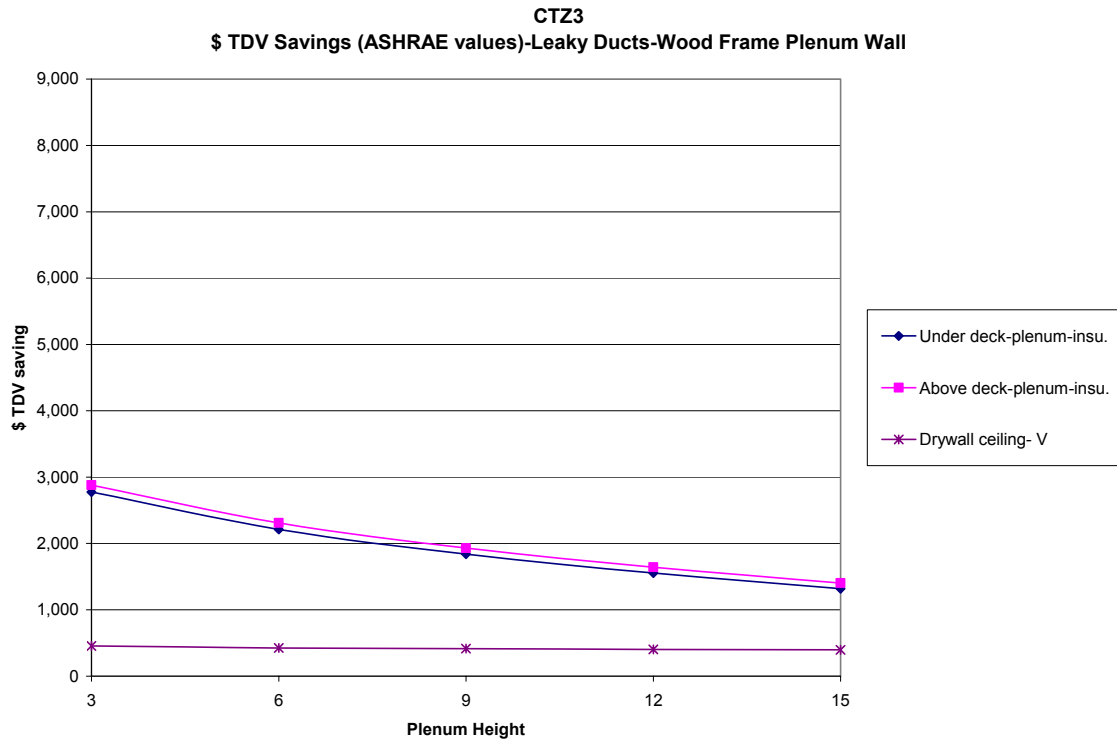


Figure 33: TDV savings with varying plenum heights (ASHRAE values)-Climate zone 3

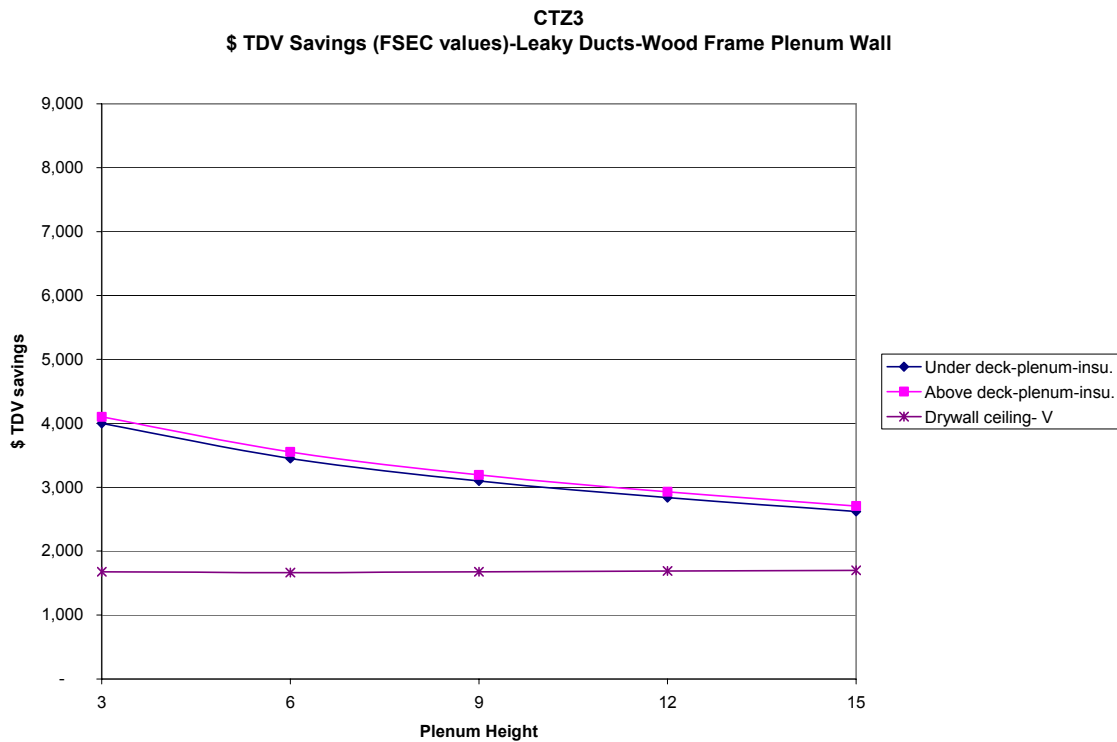


Figure 34: TDV savings with varying plenum heights (FSEC values)-Climate zone3

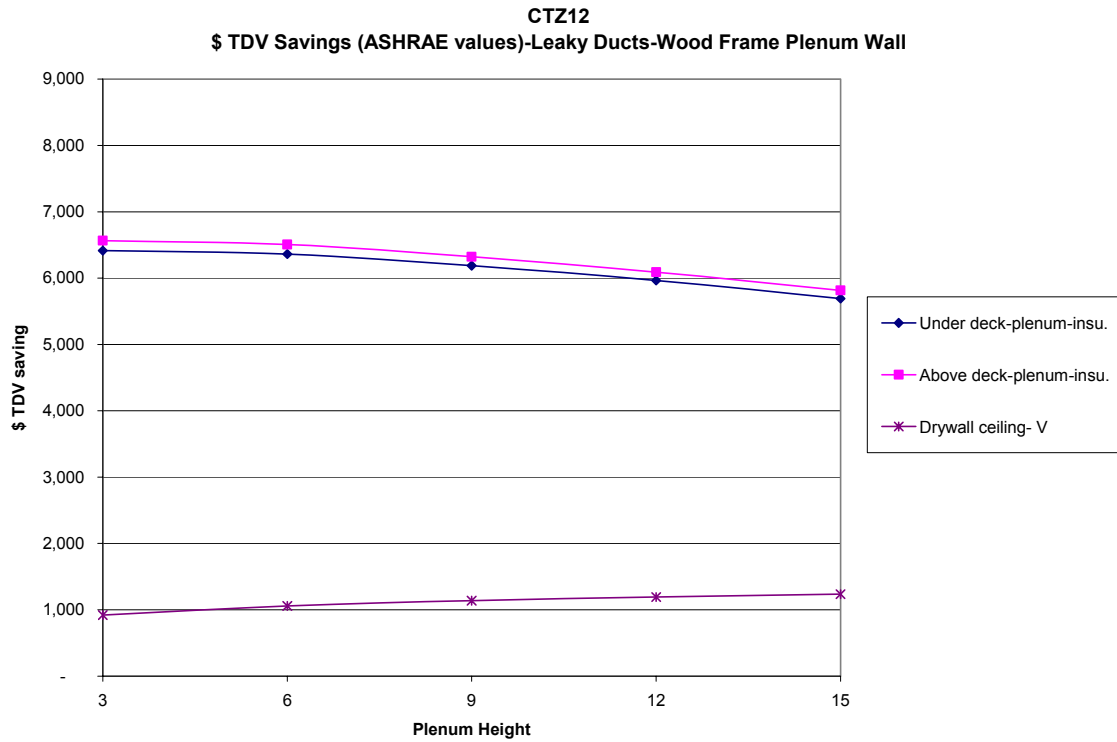


Figure 35: TDV savings with varying plenum heights (ASHRAE values)-Climate zone 12

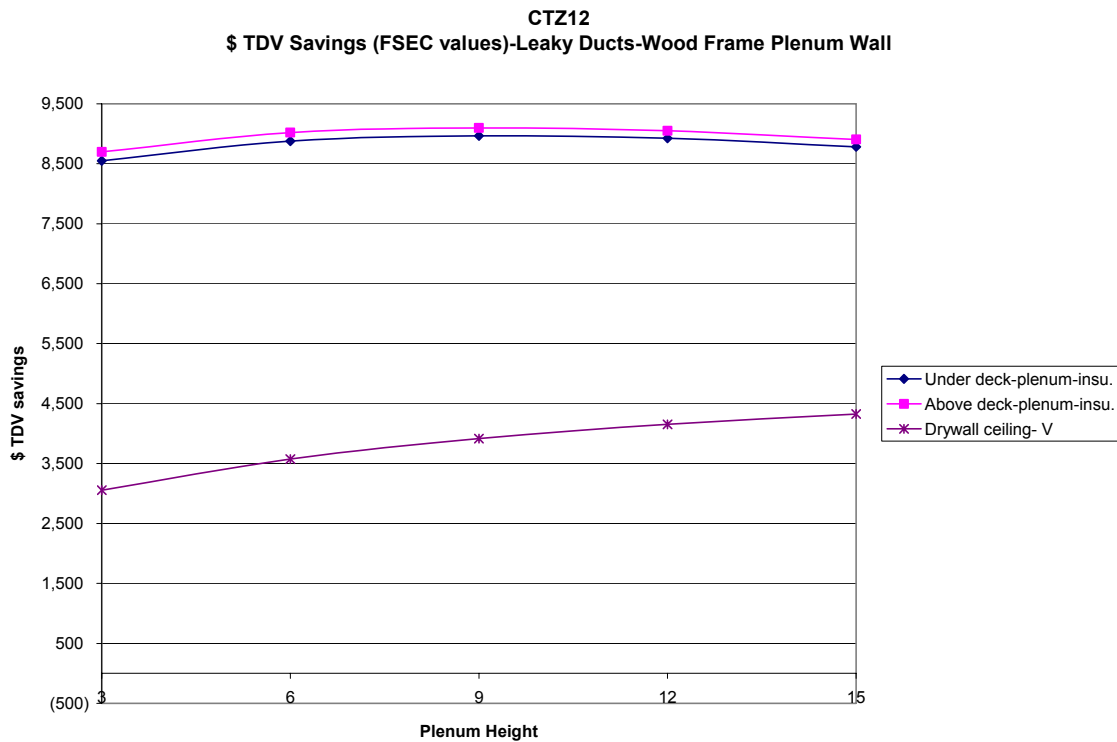


Figure 36: TDV savings with varying plenum heights (FSEC values)-Climate zone 12

Benefit Cost

The benefit cost analysis was done based on the TDV savings and the difference in the material costs of all the roofing insulation options as compared to lay-in insulation costs. The description of benefit cost ratio is described in introduction paragraph of the Results section. The following tables show the benefit cost ratios for climate zone 3, along with a summary of benefit cost ratio of all the five climate zones under study. The benefit cost ratios for climate zone 12 is given in Appendix C.

One thing to note is that there is a difference in the initial cost of 'frame wall' when compared to the 'tilt up mass wall' (refer to Table 15). This difference is because tilt up requires an extra cost for stick pins to place the insulation while frame wall does not have that extra cost.

1. Benefit cost ratios of sealing and insulating ducts for insulated roofs, drywall and lay-in ceilings

This section describes the benefit cost ratios for tightening the ducts and adding duct insulation (from R 4.2 to R 8) for insulated roof deck, drywall and lay-in ceiling conditions for climate zones 3 and 12. The benefit cost ratios were calculated for the plenum heights of 3ft, 6ft, 9ft, 12ft and 15ft.

Table 44 shows cost effectiveness in tightening ducts for all plenum heights for climate zone 3. The insulated roofs are cost effective for plenum height of 9 feet and above.

Table 44: Benefit cost ratio of sealing ducts and increasing duct insulation from R 4.2 to R 8 - Climate Zone 3

CTZ3					
Benefit cost ratio for tightening ducts for all insulation conditions					
Plenum Hts	Insulated Plenum Wall		Uninsulated Plenum Wall		
	Under deck-plenum-insu.	Above deck-plenum-insu.	Drywall ceiling-V	Lay-in-V ASHRAE	Lay-in-V-FSEC
3	0.76	0.71	4.32	4.07	3.43
6	0.96	0.91	4.34	4.37	4.14
9	1.14	1.09	4.31	4.49	4.48
12	1.31	1.26	4.28	4.55	4.70
15	1.48	1.43	4.26	4.59	4.85

Table 45 indicates that for climate zone 12, the insulated roofs show cost effectiveness for heights above 3 feet, while the insulated ceilings indicate cost effectiveness for all plenum heights.

Table 45: Benefit cost ratio of sealing ducts and increasing duct insulation from R 4.2 to R 8 - Climate Zone 12

CTZ12					
Benefit cost ratio for Tightening Ducts for all insulation conditions					
	Insulated Plenum Wall		Uninsulated Plenum Wall		
Plenum Hts	Under deck-plenum-insu.	Above deck-plenum-insu.	Drywall ceiling-V	Lay-in-V-ASHRAE	Lay-in-V-FSEC
3	0.93	0.85	8.25	7.59	6.07
6	1.17	1.09	9.26	9.04	8.10
9	1.41	1.33	9.79	9.81	9.29
12	1.67	1.59	10.11	10.31	10.08
15	1.98	1.90	10.32	10.64	10.64

2. Benefit Cost Ratios of insulated roof decks with leaky ducts (R 4.2) versus insulated lay-in ceilings with tight ducts (R 8)-Climate zone 3

The second case determines benefit cost ratios for insulated roof deck conditions with leaky ducts (R4.2) versus insulated lay-in ceilings with tight ducts (R 8). The benefit cost ratios were calculated for the plenum heights of 3ft, 6ft, 9ft, 12ft and 15ft.

Table 46 (ASHRAE results) shows that for climate zone 3, the insulated roof deck is cost effective only for 3 feet plenum heights.

Table 46: Benefit cost ratio of insulated roofs with leaky ducts (R4.2) versus insulated lay-in ceiling with tight ducts (R 8) using ASHRAE values -Climate zone 3

CTZ3		
Benefit cost ratio-insul. roofs(leaky ducts) vs insul. Ceiling(tight ducts)-ASHRAE		
Plenum Hts	Under deck-plenum-insu.	Above deck-plenum-insu.
3	1.04	0.24
6	(0.69)	(0.15)
9	(0.93)	(0.32)
12	(0.96)	(0.40)
15	(0.93)	(0.45)

Table 47 (FSEC results) indicates a benefit cost below 9 feet plenum height for 'under deck insulated roof and below 6' for 'above deck' insulated roof.

Table 47: Benefit cost ratio of insulated roofs with leaky ducts (R4.2) versus insulated lay-in ceiling with tight ducts (R 8) using FSEC values -Climate zone 3

CTZ3		
Benefit cost ratio-insul. roofs(leaky ducts) vs insul. Ceiling(tight ducts)-FSEC		
Plenum Hts	Under deck-plenum-insu.	Above deck-plenum-insu.
3	6.48	1.15
6	1.57	0.51
9	0.43	0.20
12	(0.00)	0.03
15	(0.20)	(0.07)

Table 48 shows the benefit cost ratio for climate zone 12 with ASHRAE values. The benefit cost is below 9 feet plenum height for under deck insulated roof and below 6 feet plenum height for above deck insulated roof. The FSEC results (Table 49) show cost effectiveness for all plenum heights for both the insulation conditions.

Table 48: Benefit cost ratio of insulated roofs with leaky ducts (R4.2) versus insulated lay-in ceiling with tight ducts (R 8) using ASHRAE values -Climate zone 12

CTZ12		
Benefit cost ratio-insul. roofs(leaky ducts) vs insul. Ceiling(tight ducts)-ASHRAE		
Plenum Hts	Under deck-plenum-insu.	Above deck-plenum-insu.
3	5.64	1.10
6	1.40	0.50
9	0.30	0.17
12	(0.16)	(0.03)
15	(0.41)	(0.18)

Table 49: Benefit cost ratio of insulated roofs with leaky ducts (R4.2) versus insulated lay-in ceiling with tight ducts (R 8) using FSEC values -Climate zone 12

CTZ12		
Benefit cost ratio-insul. roofs(leaky ducts) vs insul. Ceiling(tight ducts)-FSEC		
Plenum Hts	Under deck-plenum-insu.	Above deck-plenum-insu.
3	15.21	2.81
6	6.11	1.95
9	3.42	1.43
12	2.17	1.07
15	1.45	0.81

3. Benefit Cost Ratio for Insulated roof decks and drywall ceiling with tight ducts (R 8) versus insulated lay-in ceiling with tight ducts (R 8)

Table 50 shows the benefit cost ratios for climate zone 3 for insulated roof decks and drywall ceilings with tight ducts (R 8) versus insulated lay-in ceilings with tight ducts for the plenum heights of 3ft, 6ft, 9ft, 12ft and 15ft.

The results indicate no cost effectiveness for any insulation conditions for all plenum heights for ASHRAE values. In case of FSEC values, 'under deck' insulated roof indicate cost effectiveness below 9 feet and 'above deck' indicates for only 3 feet plenum height.

Table 50: Benefit cost ratio of insulated roofs and drywall ceilings with tight ducts (R 8) versus insulated lay-in ceilings with tight ducts (R 8) using ASHRAE values- Climate zone 3

CTZ3			
Benefit cost ratio- insul. Roof/drywall (tight ducts) vs insul. Layin ceiling (tight duct)- ASHRAE			
Plenum Hts	Under deck-plenum-insu.	Above deck-plenum-insu.	Drywall ceiling-V
3	0.85	0.36	0.20
6	0.14	0.09	0.14
9	(0.10)	(0.03)	0.11
12	(0.20)	(0.09)	0.09
15	(0.25)	(0.13)	0.08

Table 51: Benefit cost ratio of insulated roofs and drywall ceilings with tight ducts (R 8) versus insulated lay-in ceilings with tight ducts (R 8) using FSEC values - Climate zone 3

CTZ3			
Benefit cost ratio- insul. Roof/drywall (tight ducts) vs insul. Layin ceiling (tight duct)- FSEC			
Plenum Hts	Under deck-plenum-insu.	Above deck-plenum-insu.	Drywall ceiling-V
3	2.64	1.03	0.76
6	1.26	0.60	0.62
9	0.71	0.38	0.54
12	0.44	0.26	0.50
15	0.28	0.18	0.47

Climate zone 12 indicates cost effectiveness for insulated roofs and drywall ceiling for all plenum heights for FSEC values and cost effectiveness for specific heights with ASHRAE values.

Table 52: Benefit cost ratio of insulated roofs and drywall ceilings with tight ducts (R 8) vs insulated lay-in ceilings with tight ducts (R 8) using ASHRAE values- Climate zone 12

CTZ12 Benefit cost ratio- insul. Roof/drywall (tight ducts) vs insul. Layin ceiling (tight duct)- ASHRAE			
Plenum Hts	Under deck-plenum-insu.	Above deck-plenum-insu.	Drywall ceiling-V
3	2.56	1.03	0.44
6	1.29	0.63	0.41
9	0.72	0.40	0.39
12	0.42	0.26	0.38
15	0.23	0.16	0.37

Table 53: Benefit cost ratio of insulated roofs and drywall ceilings with tight ducts (R 8) vs insulated lay-in ceilings with tight ducts (R 8) using FSEC values- Climate zone 12

CTZ12 Benefit cost ratio- insul. Roof/drywall (tight ducts) vs insul. Layin ceiling (tight duct)- FSEC			
Plenum Hts	Under deck-plenum-insu.	Above deck-plenum-insu.	Drywall ceiling-V
3	5.87	2.31	1.50
6	3.73	1.76	1.48
9	2.65	1.41	1.46
12	2.01	1.17	1.45
15	1.59	0.98	1.44

RECOMMENDATIONS

In evaluating the cost-effectiveness of requiring insulation at the roof deck in lieu of lay-in insulation above T-bar ceilings, the following principles were applied:

- Insulation below roof deck was considered as the bench mark for evaluation. Above deck insulation is more expensive than below deck insulation. Above deck insulation is chosen primarily to protect single ply roofing systems over certain deck materials (such as metal decks). Above deck insulation is also often used in conjunction with return plenums or when the roof deck is exposed to view. The cost-effectiveness analysis need not pay for the other amenities yielded by above deck insulation. Below deck insulation is the least cost method of providing the energy savings from roof insulation, and is the basis for recommendations regarding requiring alternatives to lay-in insulation.
- A range of infiltration rates were looked at for lay-in insulation conditions—mainly ASHRAE values and FSEC values. The FSEC rates were based on more documented research. Hence the recommendations made are based on FSEC results.
- Desirability of a single insulation position requirement. In mild climates, the benefits from insulating the roof deck are less and are cost-justified for a smaller range of plenum heights in mass buildings. Insulating the roof decks of frame wall construction buildings were cost-justified only in extreme climate zones, while for mild climates, it was cost effective above 9 feet plenum height. Having insulation position requirements that are a function of wall construction and climate zone seem to be an unnecessary complexity that hinders compliance and enforcement of the building standards.
- Desirability of allowing lay-in insulation for small conditioned offices or other spaces in unconditioned warehouse and industrial buildings. The cost of framing in the perimeter of these spaces up to a 12 feet or higher ceiling plenum was not cost-effective.
- Insulated ceilings (both acoustic tiles and drywall) indicate cost effectiveness in tightening and increasing R-value of insulation to ducts (from R4.5 to R 8).
- When the average height of the space between the ceiling and the roof is greater than 12 feet, insulation placed in direct contact with the ceilings having movable ceiling tiles shall be an acceptable method of reducing heat loss from a conditioned space because of the expense of the alternatives.
- Since lay-in insulation is essentially an undesirable location as related to energy consumption, its use should be minimized and allowed only for exceptional cases such as small offices in warehouse buildings. Thus lay-in insulation should be limited to spaces no greater than 2,000 SF of area.

Insulated Drywall Ceilings

- Based on our analysis of results with FSEC infiltration rates, Insulated drywall ceilings are cost-effective only for frame construction in extreme climate zones. The drywall ceilings were not cost effective for both the mass wall conditions studied, when compared to insulated roof decks.
- Drywall costs are significantly higher than the standard grade T-bar ceilings.
- TDV energy savings of insulated drywall ceilings were comparable to the insulated roof deck.
- Even though insulation on drywall ceiling has higher 'initial' Life Cycle Costs, the designers should have the flexibility to use drywall ceilings as an option.

Plenum Heights where Insulated Roofs are Cost-Effective

The results sections in this report for each wall construction type detail the cost-effectiveness of various combinations of climate zone, wall mass, fixture type etc. The general conclusions for cost-effectiveness are:

- For mild climates (CTZ 3, 6): roof insulation is cost-effective when the plenum heights in mass buildings and frame wall buildings are less than 9 feet tall.
- For warmer climates (CTZ 10, 12, 14): roof insulation is cost-effective for all wall types for plenum heights up to 12 feet tall and in some cases (such as frame walls and mass walls not needing insulation) up to the maximum height we considered - 15 feet.

Given that most of the nonresidential construction activity is occurring in the warmer climate zones and the consideration discussed above it was decided that 12 feet is an appropriate plenum height above which lay-in insulation would be acceptable.

Proposed Standards Language

The following Standards language has been proposed for the California building efficiency standards (Title 24) that would take effect in 2005¹⁶:

SECTION 118 - MANDATORY REQUIREMENTS FOR INSULATION AND COOL ROOFS

(e) Placement of roof/ceiling insulation in nonresidential and high-rise residential buildings. Insulation installed to limit heat loss and gain through the top of conditioned spaces shall comply with the following:

1. Insulation shall be installed in direct contact with a continuous roof or ceiling which is sealed to limit infiltration and exfiltration as specified in Section 117,

¹⁶ California Energy Commission, 2005 Energy Efficiency Standards for residential and Nonresidential Buildings Workshop Draft #3, Feb4, 2003. P400-03-001D3.

including but not limited to placing insulation either above or below the roof deck or on top of a drywall ceiling; and

2. When insulation is installed at the roof in nonresidential buildings, fixed vents or openings to the outdoors or to unconditioned spaces shall not be installed and the space between the ceiling and the roof is either directly or indirectly conditioned space and shall not be considered an attic for the purposes of complying with CBC Section 1505.3; and
3. Insulation placed on top of a suspended ceiling with removable ceiling panels shall be deemed to have no affect on envelope heat loss; and
4. Insulation shall be installed below the roofing membrane or layer used to seal the roof from water penetration unless the insulation has a maximum water absorption of 0.3 percent by volume when tested according to ASTM Standard C 272.

EXCEPTION to Section 118(e) 3: When there are conditioned spaces with a combined floor area no greater than 2,000 square feet in an otherwise unconditioned building, and when the average height of the space between the ceiling and the roof over these spaces is greater than 12 feet, insulation placed in direct contact with a suspended ceiling with removable ceiling panels shall be an acceptable method of reducing heat loss from a conditioned space and shall be accounted for in heat loss calculations.

Modeling Lay-in Insulation - Future Research

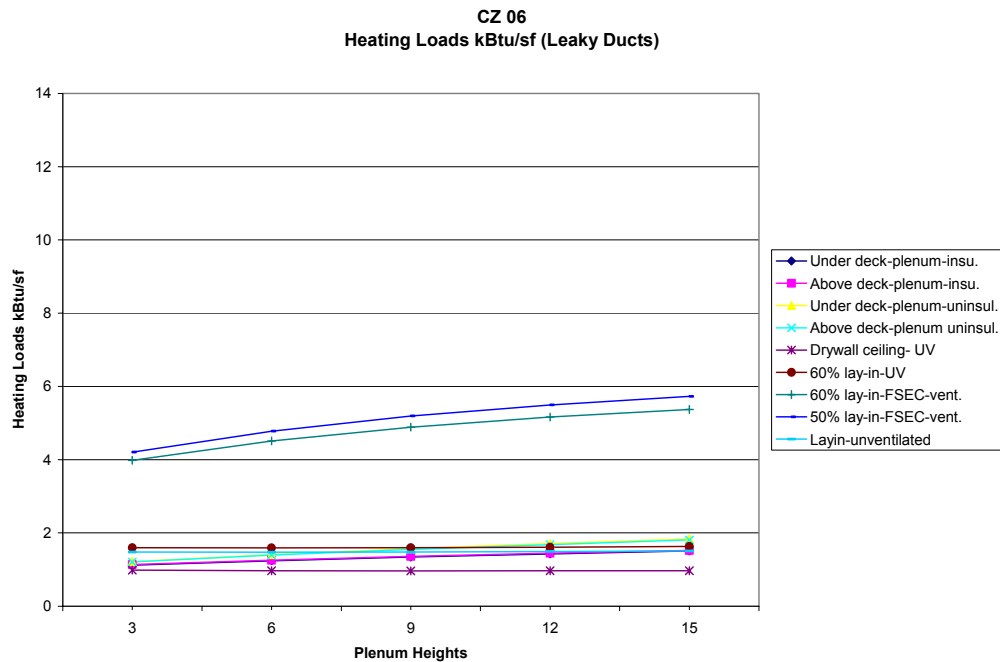
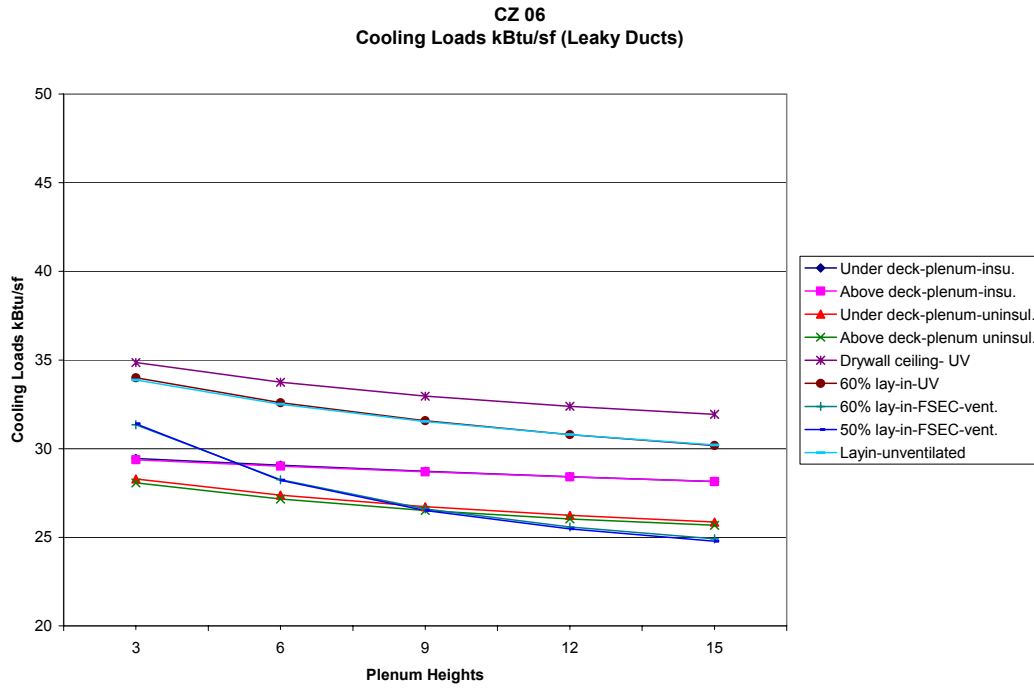
Assumptions concerning the air infiltration rates across suspended acoustic tile ceilings have a large impact on the outcome. Similarly, the energy impacts of envelope tightness on air exchange rates is not entirely clear-especially in conjunction with increased concern about indoor air quality. This area of research is still under development. Research on the interaction between T-bar ceilings or their alternatives and fixed damper settings on small HVAC units could provide insights that yield energy savings and indoor air quality benefits.

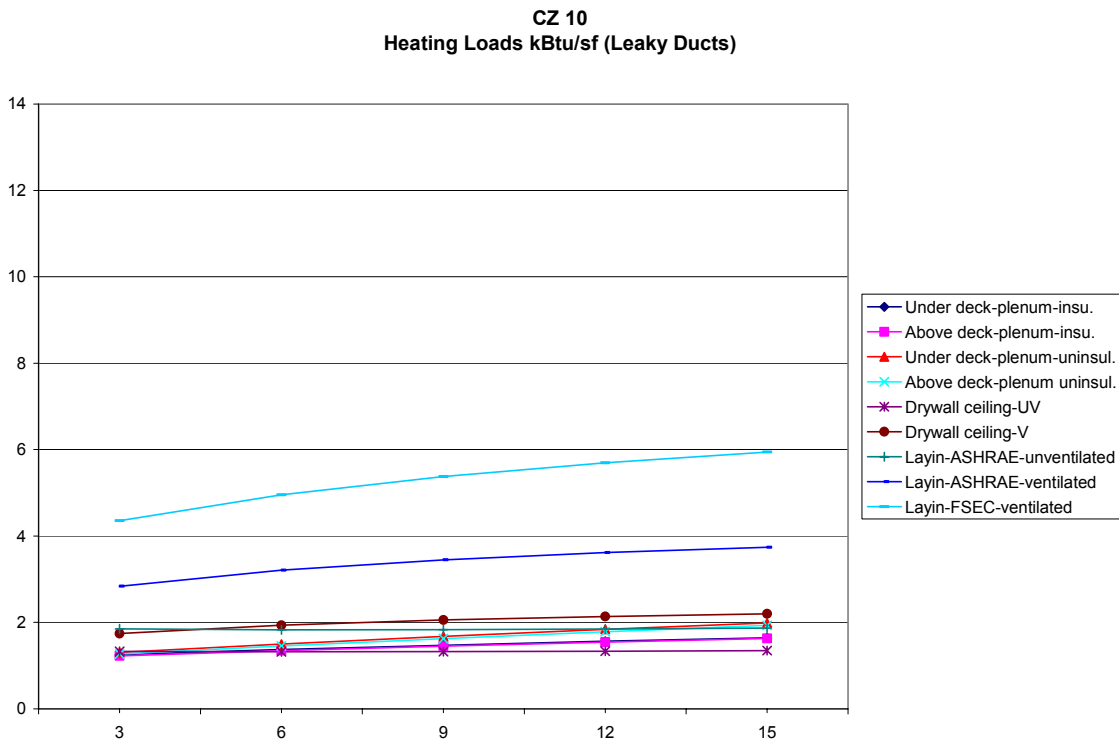
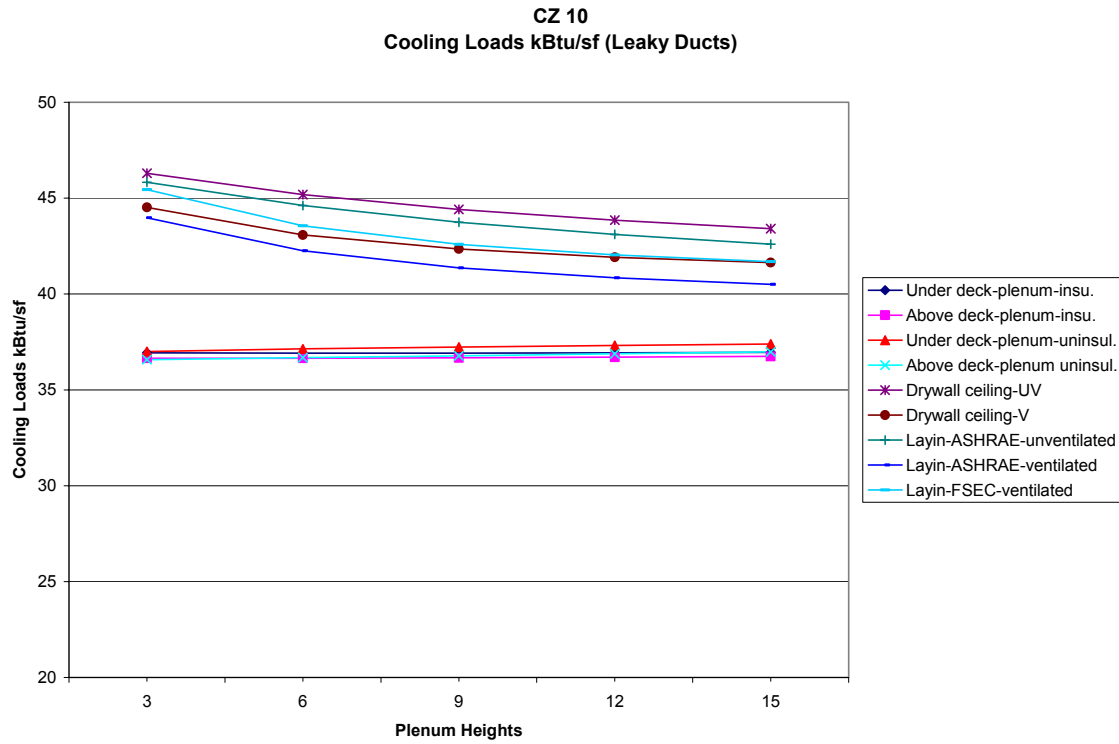
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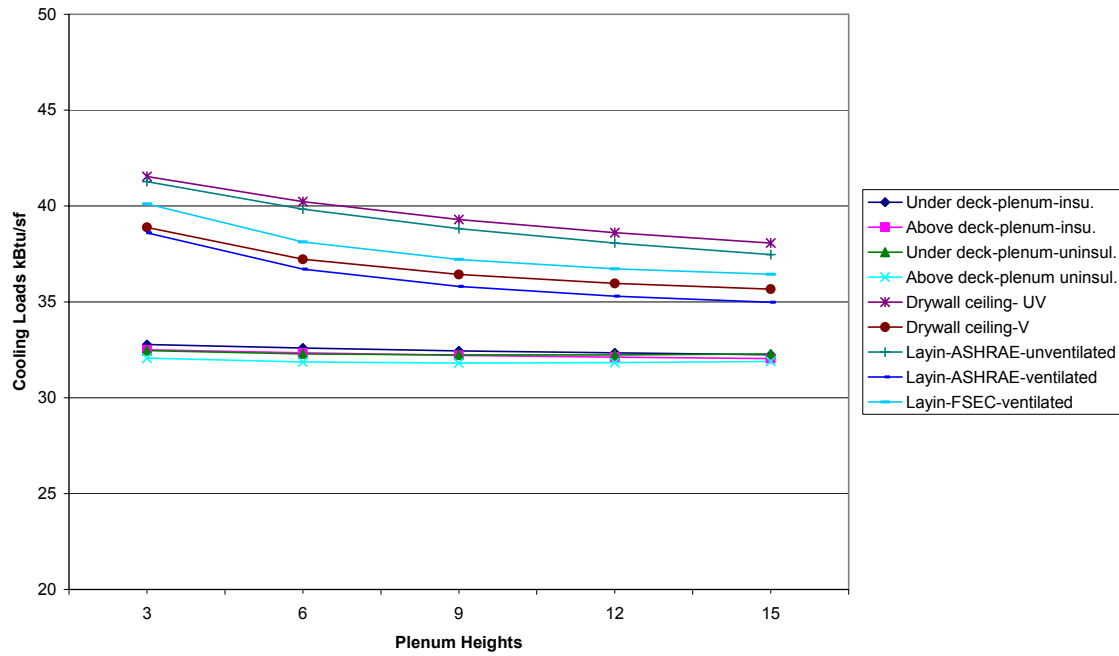
Appendix. A - Mass Wall with Troffers

Energy Analysis

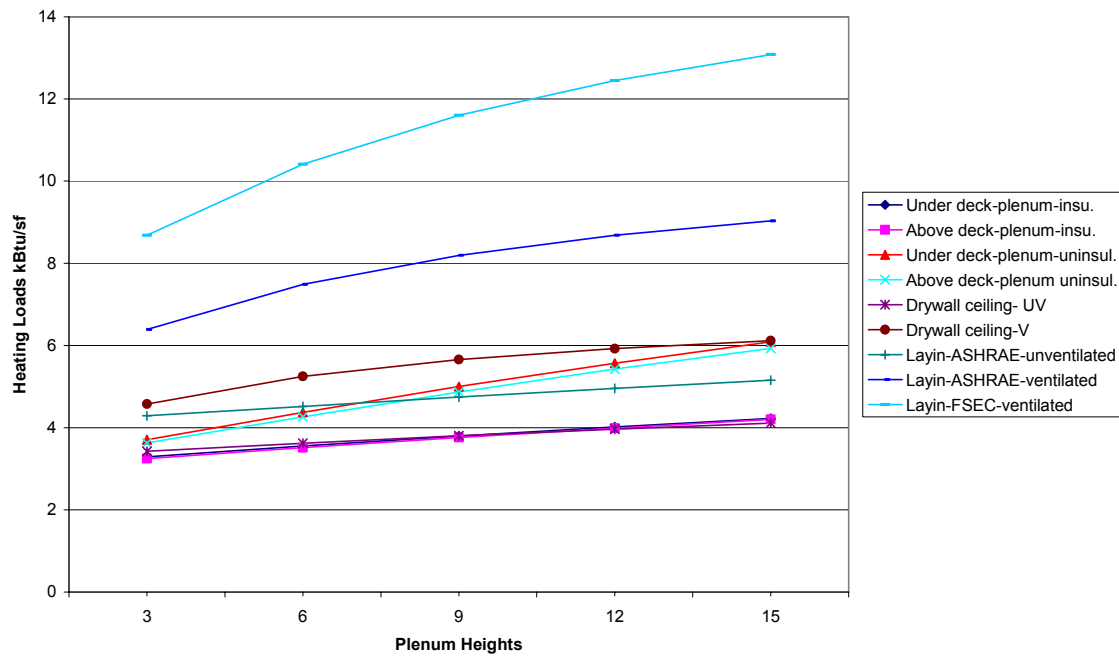




CZ 14
Cooling Loads kBtu/sf (Leaky Ducts)

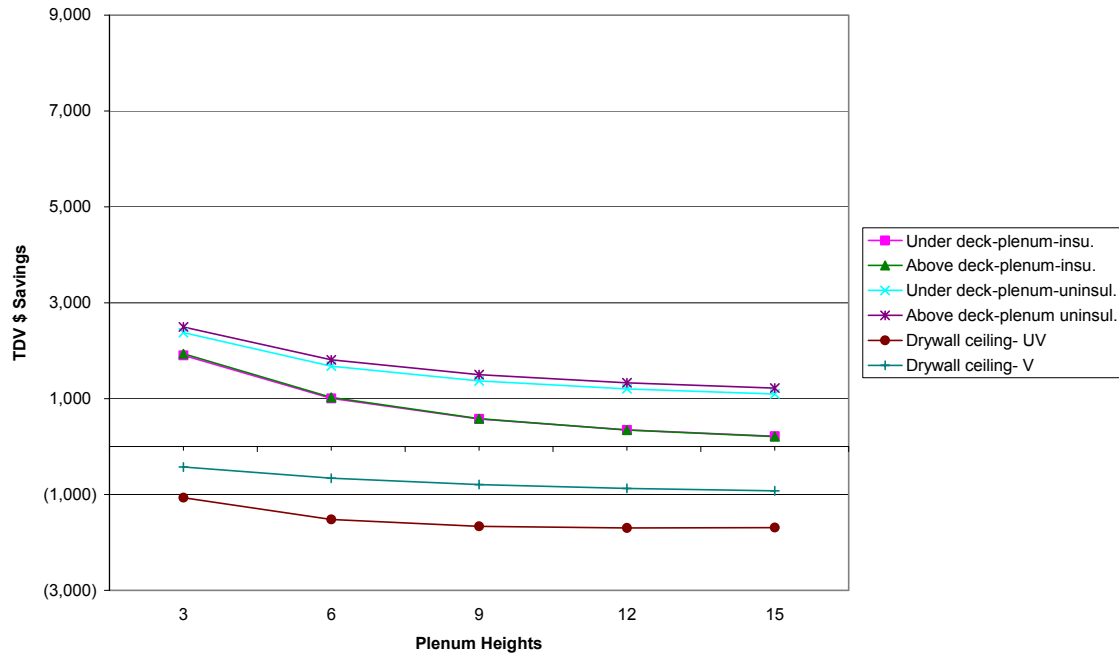


CZ 14
Heating Loads kBtu/sf (Leaky Ducts)

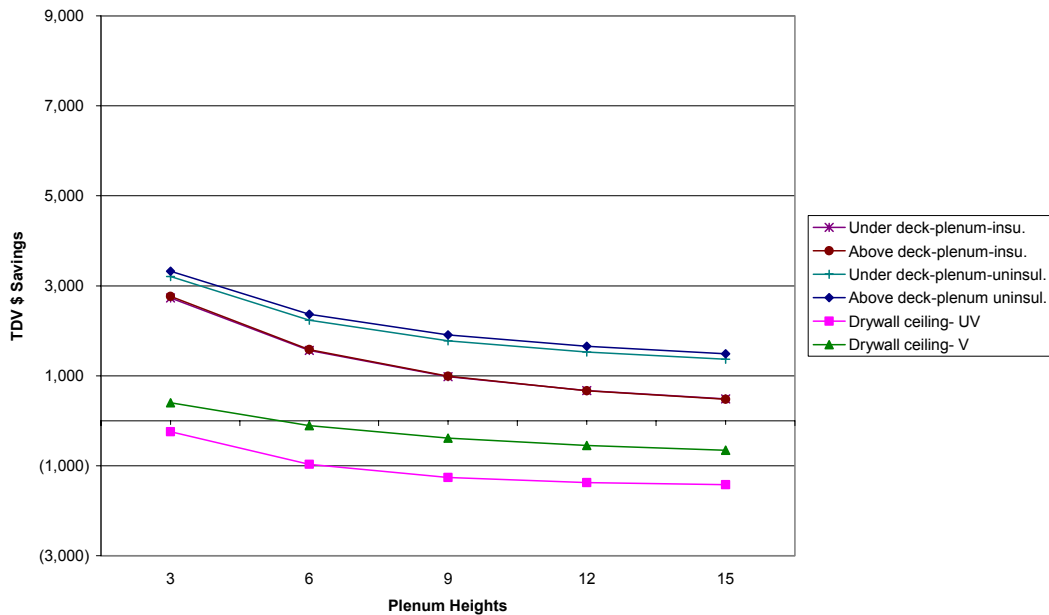


TDV Savings Analysis

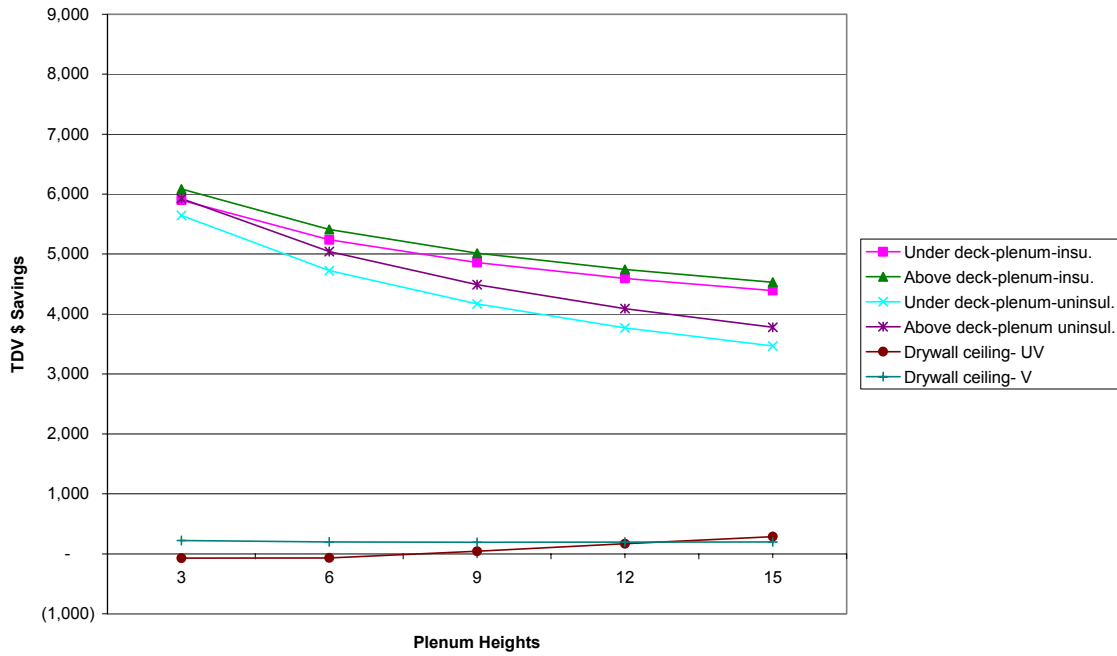
CZ 06
ASHRAE ventilated ceilings (Leaky Ducts)



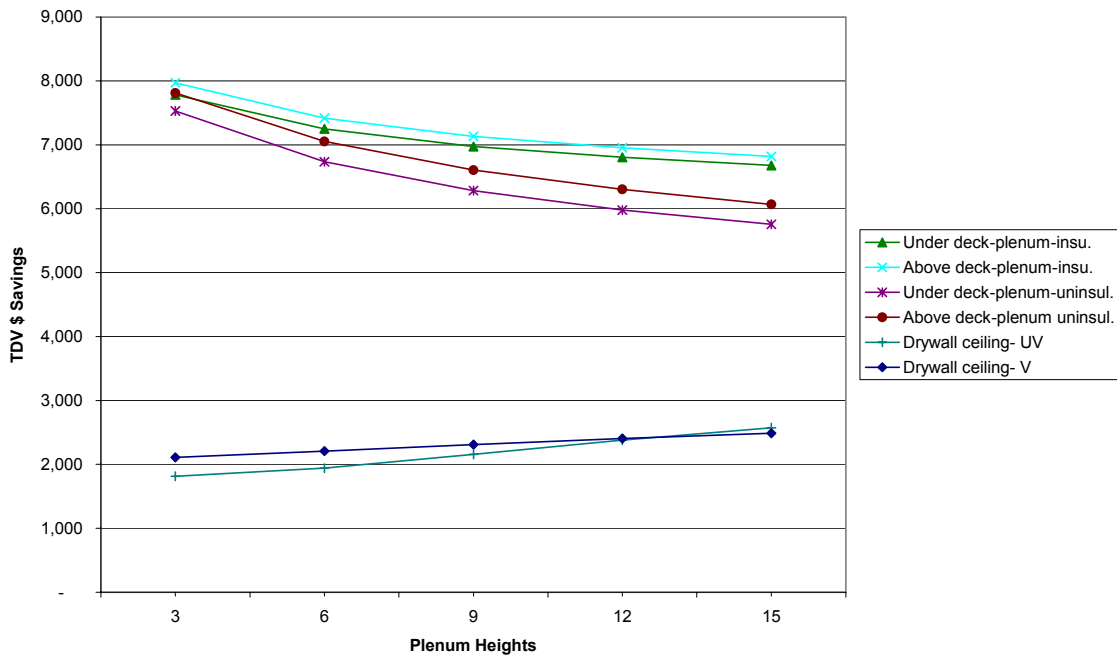
CZ 06
FSEC ventilated ceilings (Leaky Ducts)



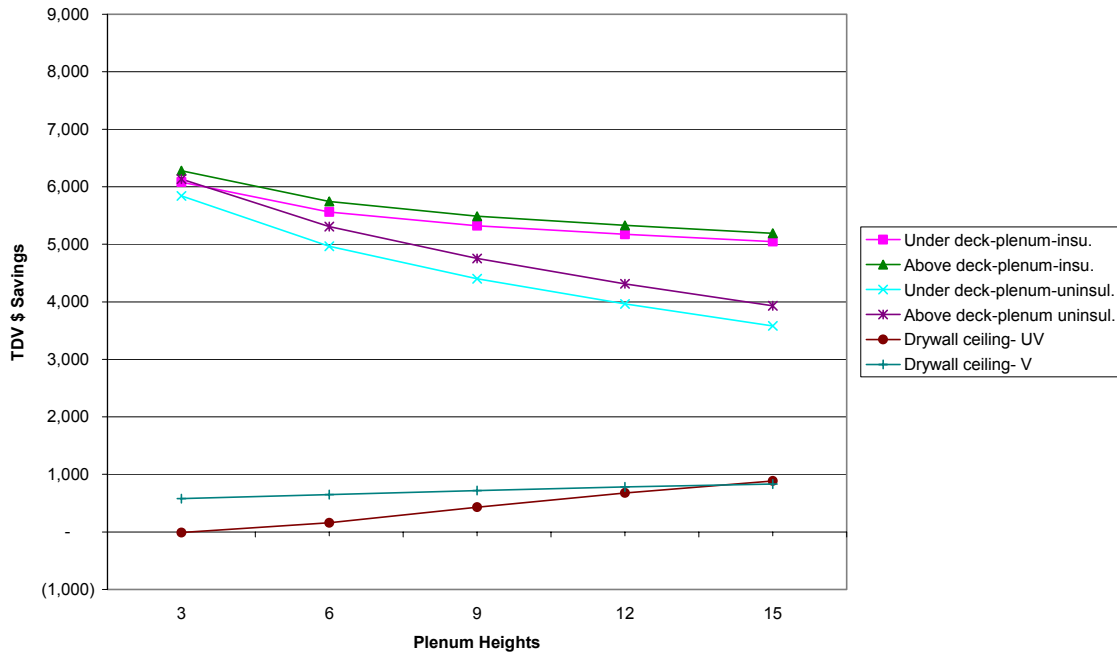
CZ 10
ASHRAE ventilated ceilings (Leaky Ducts)



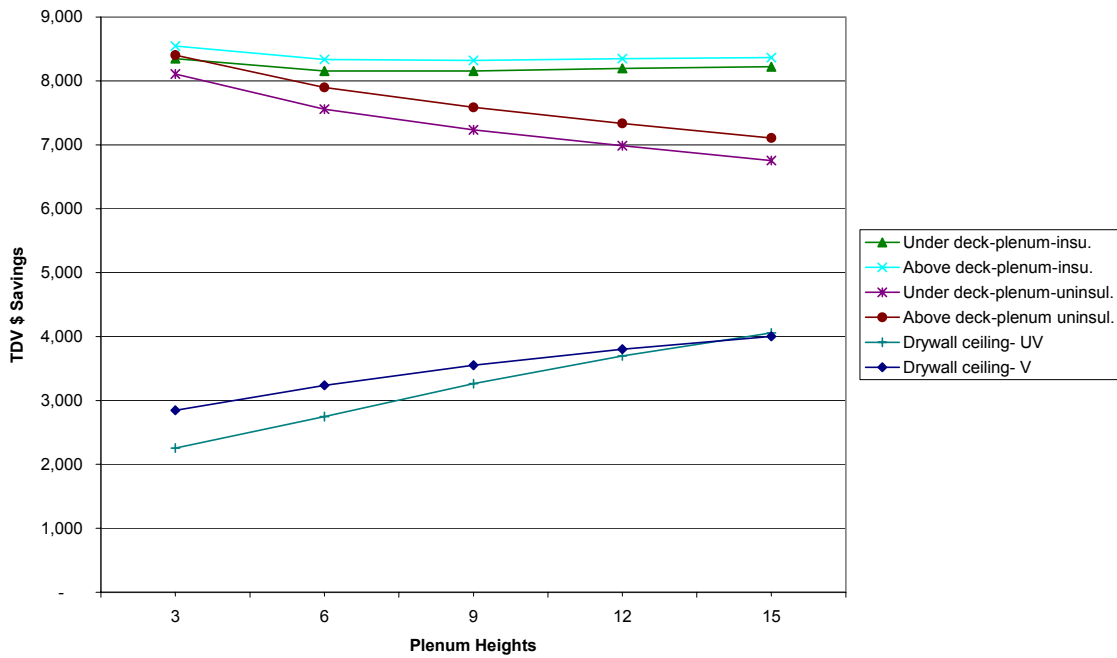
CZ 10
FSEC ventilated ceilings (Leaky Ducts)



CZ 14
ASHRAE ventilated ceilings (Leaky Ducts)



CZ 14
FSEC ventilated ceilings (Leaky Ducts)



Benefit Cost Ratio Analysis- Climate Zones 6, 10, 12, 14

Climate Zone 6

1. Benefit cost ratios of tightening and adding insulation to ducts for insulated roofs, drywall and lay-in ceilings from leaky (R 4.2) to tight (R 8)

Table 54: Benefit cost ratios of tightening and adding insulation to ducts for insulated roofs and drywall and lay-in ceilings from leaky (R 4.2) to tight (R 8) - Climate Zone 6

CTZ6 Benefit cost ratio for Tightening Ducts for all insulation conditions									
Plenum Hts	Insulated Plenum Wall		Uninsulated Plenum Wall						
	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum-uninsul.	Drywall ceiling-UV	Drywall ceiling-V	Lay-in-UV	Lay-in-V-ASHRAE	Lay-in-V-FSEC
3	0.97	0.91	1.28	1.15	4.15	4.87	3.59	4.49	3.96
6	1.20	1.15	1.68	1.54	4.11	4.59	3.71	4.46	4.29
9	1.41	1.36	1.93	1.80	4.07	4.40	3.76	4.36	4.38
12	1.58	1.55	2.12	1.99	4.01	4.27	3.77	4.28	4.42
15	1.73	1.71	2.29	2.15	3.96	4.18	3.77	4.22	4.44

2. Benefit cost ratios of insulated roof decks with leaky ducts (R 4.2) versus insulated lay-in ceilings with tight ducts (R 8)-Climate zone 3 for plenum heights of 3ft, 6ft, 9ft, 12ft and 15ft

Table 55: Benefit cost ratio of insulated roofs with leaky ducts (R4.2) versus insulated lay-in ceiling with tight ducts (R 8) using ASHRAE values -Climate zone 6

CTZ6 Benefit cost ratio-insul. roofs(leaky ducts) vs insul. Ceiling(tight ducts)-ASHRAE				
Plenum Hts	Insulated Plenum Wall		Uninsulated Plenum Wall	
	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum-uninsul.
3	(1.89)	(0.81)	(12.50)	(0.42)
6	(1.96)	(1.18)	(34.76)	(1.52)
9	(1.60)	(1.12)	(42.78)	(1.93)
12	(1.31)	(0.84)	(46.53)	(2.13)
15	(1.09)	(0.87)	(48.78)	(2.25)

Table 56: Benefit cost ratio of insulated roofs with leaky ducts (R4.2) versus insulated lay-in ceiling with tight ducts (R 8) using FSEC values -Climate zone 6

CTZ6 Benefit cost ratio-insul. roofs(leaky ducts) vs insul. Ceiling(tight ducts)-FSEC				
Plenum Hts	Insulated Plenum Wall		Uninsulated Plenum Wall	
	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.
3	0.73	0.36	27.47	1.60
6	(1.20)	(0.72)	(12.20)	(0.38)
9	(1.29)	(0.90)	(29.32)	(1.25)
12	(1.17)	(0.75)	(38.51)	(1.72)
15	(1.03)	(0.82)	(44.32)	(2.03)

3. Benefit Cost Ratio for Insulated roof decks and drywall ceiling with tight ducts (R 8) versus insulated lay-in ceiling with tight ducts (R 8)

Table 57: Benefit cost ratio of insulated roofs and drywall ceilings with tight ducts (R 8) versus insulated lay-in ceilings with tight ducts (R 8) using ASHRAE values for plenum heights of 3ft, 6ft, 9ft, 12ft and 15ft- Climate zone 6

CTZ6 Benefit cost ratio- insul. Roof/drywall (tight ducts) vs insul. Layin ceiling (tight duct)- ASHRAE						
Plenum Hts	Insulated Plenum Wall		Uninsulated Plenum Wall			
	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.	Drywall ceiling-UV	Drywall ceiling-V
3	(0.24)	(0.16)	0.65	0.38	(0.46)	(0.08)
6	(0.66)	(0.48)	(0.00)	0.04	(0.61)	(0.21)
9	(0.64)	(0.50)	(0.13)	(0.03)	(0.65)	(0.27)
12	(0.55)	(0.39)	(0.12)	(0.02)	(0.65)	(0.30)
15	(0.47)	(0.39)	(0.07)	(0.00)	(0.64)	(0.33)

Table 58: Benefit cost ratio of insulated roofs and drywall ceilings with tight ducts (R 8) versus insulated lay-in ceilings with tight ducts (R 8) using FSEC values for plenum heights of 3ft, 6ft, 9ft, 12ft and 15ft- Climate zone 6

CTZ6 Benefit cost ratio- insul. Roof/drywall (tight ducts) vs insul. Layin ceiling (tight duct)- FSEC						
Plenum Hts	Insulated Plenum Wall		Uninsulated Plenum Wall			
	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.	Drywall ceiling-UV	Drywall ceiling-V
3	0.87	0.57	2.49	1.37	(0.05)	0.32
6	(0.21)	(0.16)	1.04	0.60	(0.38)	0.02
9	(0.43)	(0.34)	0.49	0.31	(0.51)	(0.13)
12	(0.45)	(0.32)	0.25	0.18	(0.57)	(0.22)
15	(0.42)	(0.35)	0.14	0.11	(0.60)	(0.28)

Climate Zone 10

1. Benefit cost ratios of tightening and adding insulation to ducts for insulated roofs, drywall and lay-in ceilings from leaky (R 4.2) to tight (R 8)

Table 59: Benefit cost ratios of tightening and adding insulation to ducts for insulated roofs and drywall and lay-in ceilings from leaky (R 4.2) to tight (R 8) - Climate Zone 10

CTZ10 Benefit cost for Tightening Ducts for all insulation conditions									
Plenum Hts	Insulated Plenum Wall		Uninsulated Plenum Wall						
	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.	Drywall ceiling- UV	Drywall ceiling- V	Lay-in- UV	Lay-in-V-ASHRAE	Lay-in-V-FSEC
3	1.05	0.95	1.62	1.42	7.17	8.62	6.09	7.73	6.32
6	1.29	1.20	2.36	2.09	7.34	8.91	6.49	8.59	7.88
9	1.54	1.45	2.94	2.63	7.44	9.02	6.75	9.00	8.74
12	1.78	1.70	3.42	3.10	7.50	9.09	6.93	9.26	9.31
15	2.00	1.91	3.82	3.51	7.55	9.14	7.08	9.45	9.72

2. Benefit cost ratios of insulated roof decks with leaky ducts (R 4.2) versus insulated lay-in ceilings with tight ducts (R 8)-Climate zone 3 for plenum heights of 3ft, 6ft, 9ft, 12ft and 15ft

Table 60: Benefit cost ratio of insulated roofs with leaky ducts (R4.2) versus insulated lay-in ceiling with tight ducts (R 8) using ASHRAE values -Climate zone 10

CTZ10 Benefit cost ratio-insul. roofs(leaky ducts) vs insul. ceiling(tight ducts)-ASHRAE				
Plenum Hts	Insulated Plenum Wall		Uninsulated Plenum Wall	
	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.
3	2.59	0.70	Infinite *	0.82
6	0.04	0.09	43.28	(0.11)
9	(0.41)	(0.14)	113.14	(0.64)
12	(0.52)	(0.25)	161.36	(1.01)
15	(0.55)	(0.30)	197.11	(1.29)

Table 61: Benefit cost ratio of insulated roofs with leaky ducts (R4.2) versus insulated lay-in ceiling with tight ducts (R 8) using FSEC values -Climate zone 10

CTZ10 Benefit cost ratio-insul. roofs(leaky ducts) vs insul. Ceiling(tight ducts)-FSEC				
Plenum Hts	Insulated Plenum Wall		Uninsulated Plenum Wall	
	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.
3	8.80	2.16	Infinite *	2.73
6	2.75	1.12	Infinite *	1.58
9	1.26	0.66	Infinite *	0.93
12	0.67	0.42	Infinite *	0.49
15	0.37	0.27	6.71	0.17

3. Benefit Cost Ratio for Insulated roof decks and drywall ceiling with tight ducts (R 8) versus insulated lay-in ceiling with tight ducts (R 8)

Table 62: Benefit cost ratio of insulated roofs and drywall ceilings with tight ducts (R 8) versus insulated lay-in ceilings with tight ducts (R 8) using ASHRAE values for plenum heights of 3ft, 6ft, 9ft, 12ft and 15ft- Climate zone 10

CTZ10 Benefit cost ratio- insul. roof/drywall (tight ducts) vs insul. layin ceiling (tight duct)- ASHRAE						
	Insulated Plenum Wall		Uninsulated Plenum Wall			
Plenum Hts	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.	Drywall ceiling- UV	Drywall ceiling- V
3	1.70	0.76	3.17	0.99	(0.18)	0.23
6	0.54	0.31	1.59	0.54	(0.30)	0.12
9	0.19	0.14	0.88	0.32	(0.32)	0.07
12	0.05	0.06	0.47	0.20	(0.31)	0.04
15	(0.02)	0.01	0.21	0.12	(0.29)	0.02

Table 63: Benefit cost ratio of insulated roofs and drywall ceilings with tight ducts (R 8) versus insulated lay-in ceilings with tight ducts (R 8) using FSEC values for plenum heights of 3ft, 6ft, 9ft, 12ft and 15ft- Climate zone 10

CTZ10 Benefit cost ratio- insul. roof/drywall (tight ducts) vs insul. layin ceiling (tight duct)- FSEC						
	Insulated Plenum Wall		Uninsulated Plenum Wall			
Plenum Hts	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.	Drywall ceiling- UV	Drywall ceiling- V
3	4.34	1.87	7.85	2.35	0.79	1.20
6	2.16	1.14	5.72	1.73	0.55	0.98
9	1.34	0.80	4.71	1.43	0.47	0.86
12	0.95	0.61	4.13	1.26	0.45	0.80
15	0.71	0.49	3.77	1.15	0.45	0.75

Climate Zone 14

1. Benefit cost ratios of tightening and adding insulation to ducts for insulated roofs, drywall and lay-in ceilings from leaky (R 4.2) to tight (R 8)

Table 64: Benefit cost ratios of tightening and adding insulation to ducts for insulated roofs and drywall and lay-in ceilings from leaky (R 4.2) to tight (R 8) - Climate Zone 14

CTZ14 Benefit cost for Tightening Ducts for all insulation conditions									
Plenum Hts	Insulated Plenum Wall		Uninsulated Plenum Wall						
	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum-uninsul.	Drywall ceiling-UV	Drywall ceiling-V	Lay-in-UV	Lay-in-V-ASHRAE	Lay-in-V-FSEC
3	1.11	1.02	1.68	1.48	7.57	8.72	6.32	7.65	6.00
6	1.35	1.25	2.43	2.13	7.80	9.11	6.80	8.74	7.90
9	1.57	1.48	3.10	2.78	7.93	9.33	7.12	9.36	9.04
12	1.75	1.67	3.68	3.33	8.02	9.47	7.36	9.78	9.81
15	1.94	1.86	4.23	3.87	8.09	9.59	7.55	10.08	10.39

2. Benefit cost ratios of insulated roof decks with leaky ducts (R 4.2) versus insulated lay-in ceilings with tight ducts (R 8)-Climate zone 3 for plenum heights of 3ft, 6ft, 9ft, 12ft and 15ft

Table 65: Benefit cost ratio of insulated roofs with leaky ducts (R4.2) versus insulated lay-in ceiling with tight ducts (R 8) using ASHRAE values -Climate zone 14

CTZ14 Benefit cost ratio-insul. roofs(leaky ducts) vs insul. Ceiling(tight ducts)-ASHRAE				
Plenum Hts	Insulated Plenum Wall		Uninsulated Plenum Wall	
	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum-uninsul.
3	3.07	0.82	Infinite *	0.98
6	0.30	0.19	29.76	0.01
9	(0.22)	(0.05)	111.12	(0.60)
12	(0.37)	(0.16)	171.07	(1.06)
15	(0.42)	(0.22)	220.19	(1.44)

Table 66: Benefit cost ratio of insulated roofs with leaky ducts (R4.2) versus insulated lay-in ceiling with tight ducts (R 8) using FSEC values -Climate zone 14

CTZ14 Benefit cost ratio-insul. roofs(leaky ducts) vs insul. Ceiling(tight ducts)-FSEC				
Plenum Hts	Insulated Plenum Wall		Uninsulated Plenum Wall	
	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum-uninsul.
3	10.47	2.56	Infinite *	3.26
6	3.72	1.50	Infinite *	2.15
9	1.99	1.02	Infinite *	1.48
12	1.27	0.75	Infinite *	0.99
15	0.88	0.57	Infinite *	0.61

3. Benefit Cost Ratio for Insulated roof decks and drywall ceiling with tight ducts (R 8) versus insulated lay-in ceiling with tight ducts (R 8)

Table 67: Benefit cost ratio of insulated roofs and drywall ceilings with tight ducts (R 8) versus insulated lay-in ceilings with tight ducts (R 8) using ASHRAE values for plenum heights of 3ft, 6ft, 9ft, 12ft and 15ft- Climate zone 14

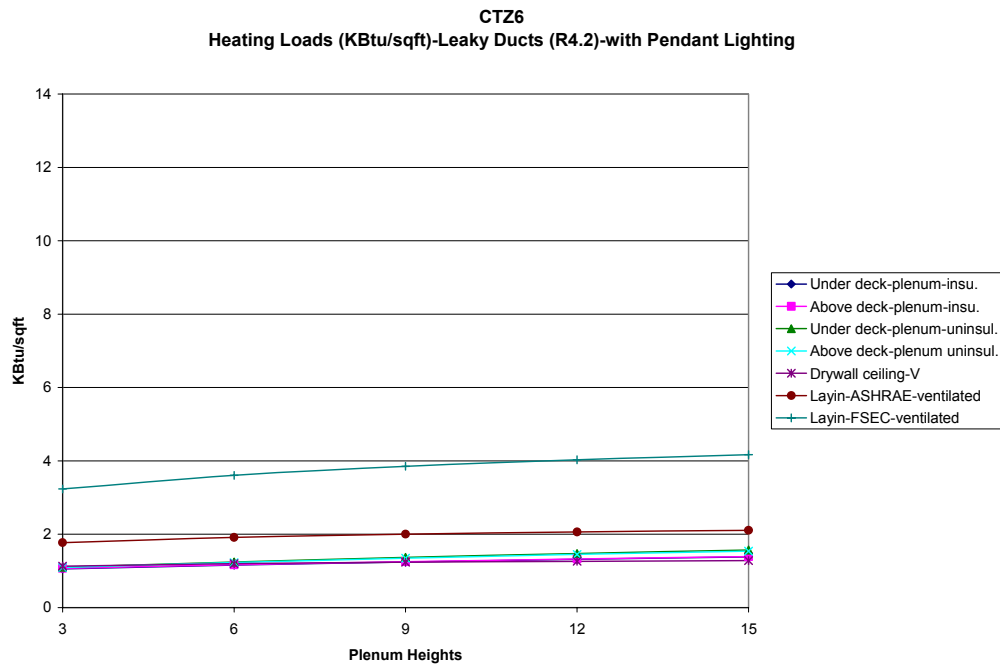
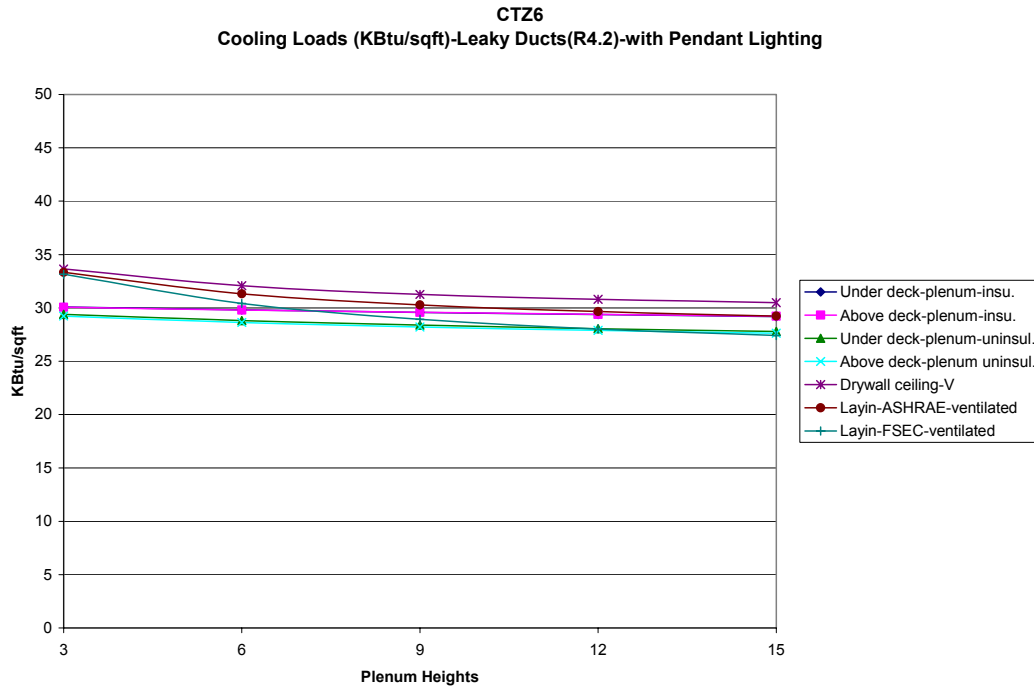
CTZ14						
Benefit cost ratio- insul. roof/drywall (tight ducts) vs insul. layin ceiling (tight duct)- ASHRAE						
	Insulated Plenum Wall		Uninsulated Plenum Wall			
Plenum Hts	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.	Drywall ceiling-UV	Drywall ceiling-V
3	1.94	0.87	3.62	1.13	(0.07)	0.38
6	0.72	0.41	1.92	0.63	(0.16)	0.29
9	0.33	0.22	1.09	0.39	(0.15)	0.24
12	0.16	0.12	0.55	0.23	(0.13)	0.22
15	0.07	0.07	0.20	0.12	(0.09)	0.20

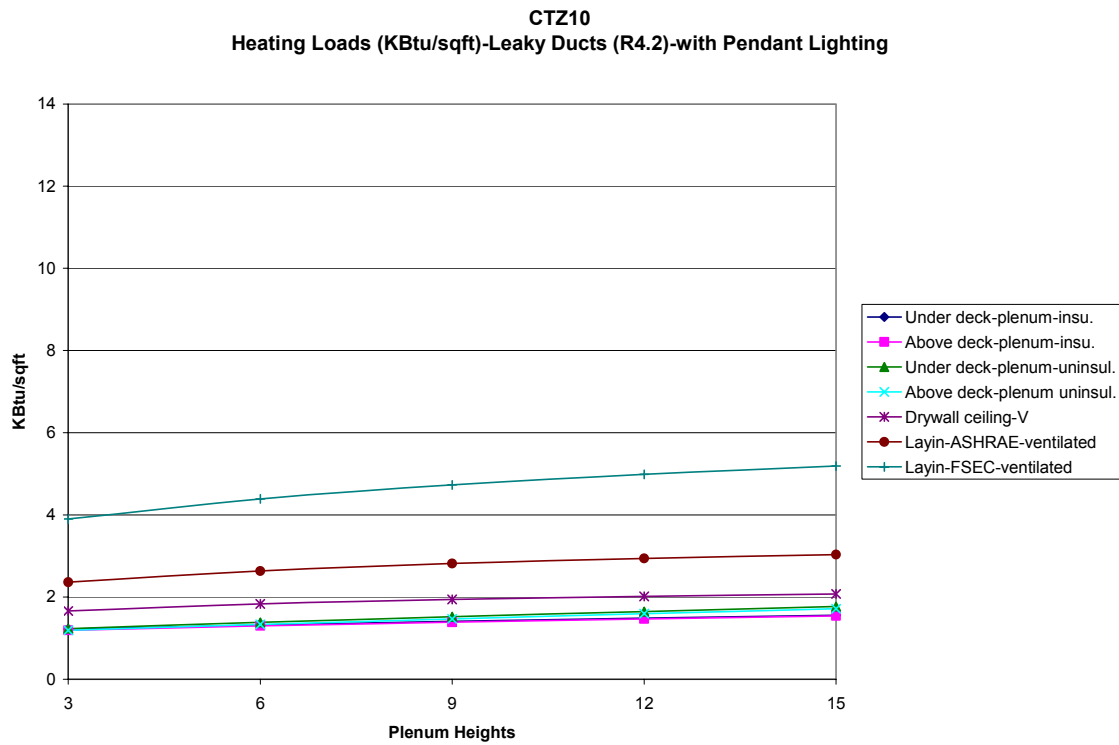
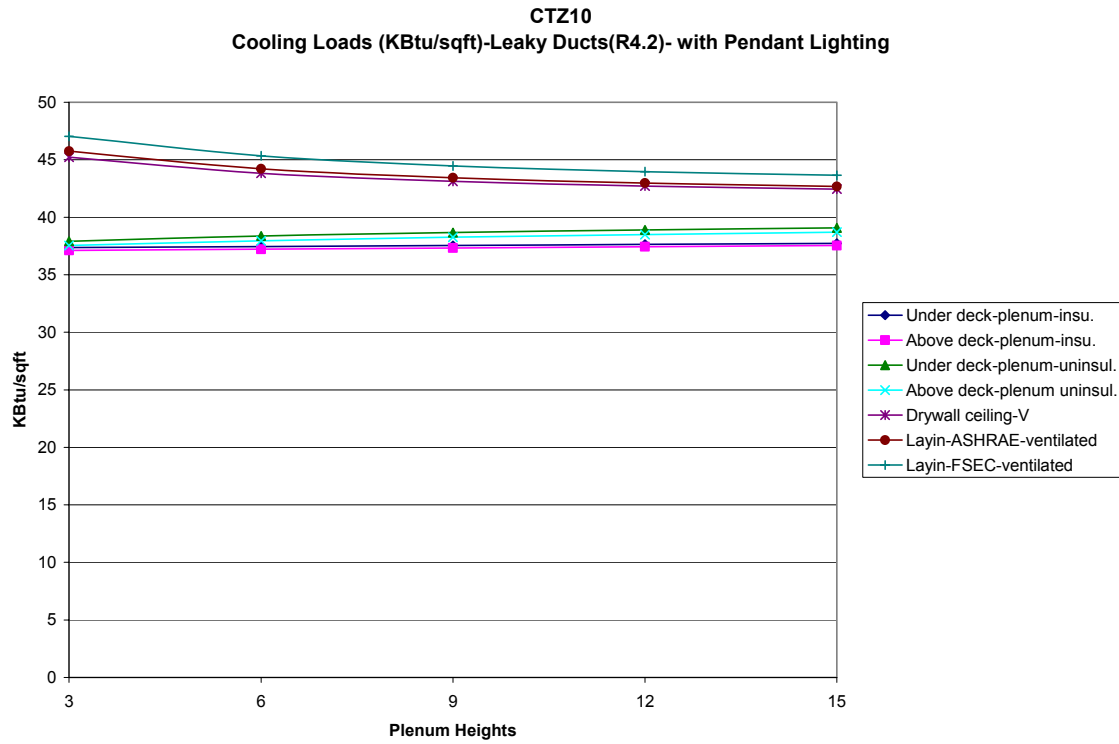
Table 68: Benefit cost ratio of insulated roofs and drywall ceilings with tight ducts (R 8) versus insulated lay-in ceilings with tight ducts (R 8) using FSEC values for plenum heights of 3ft, 6ft, 9ft, 12ft and 15ft- Climate zone 14

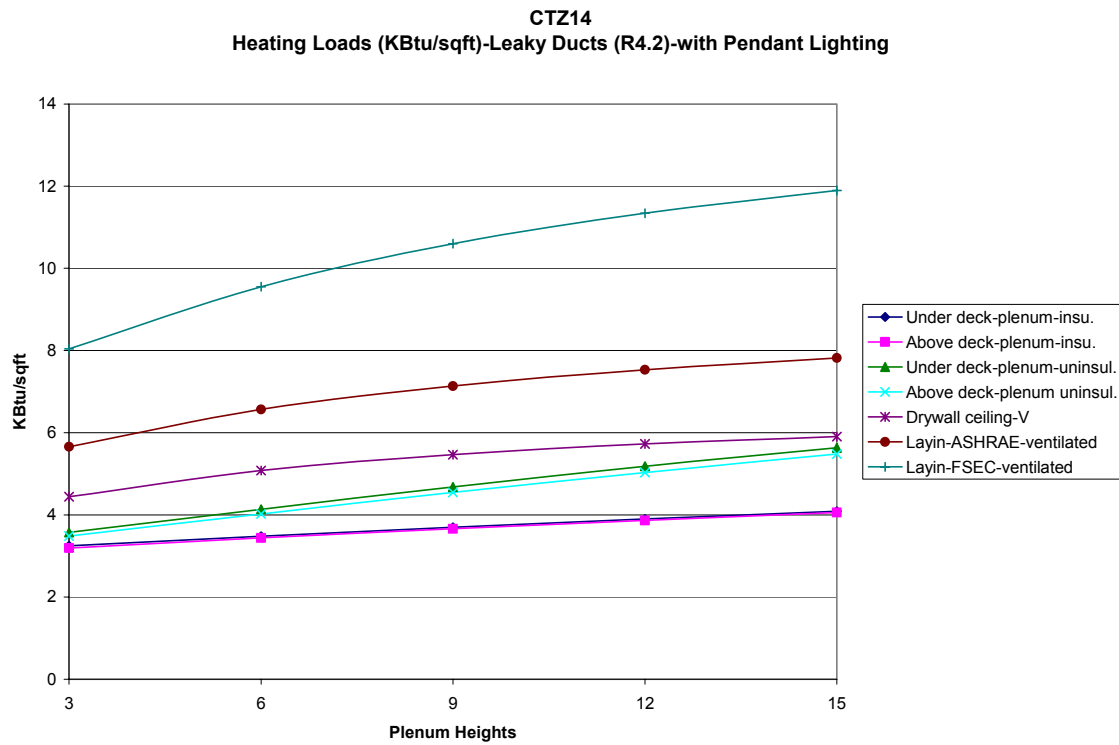
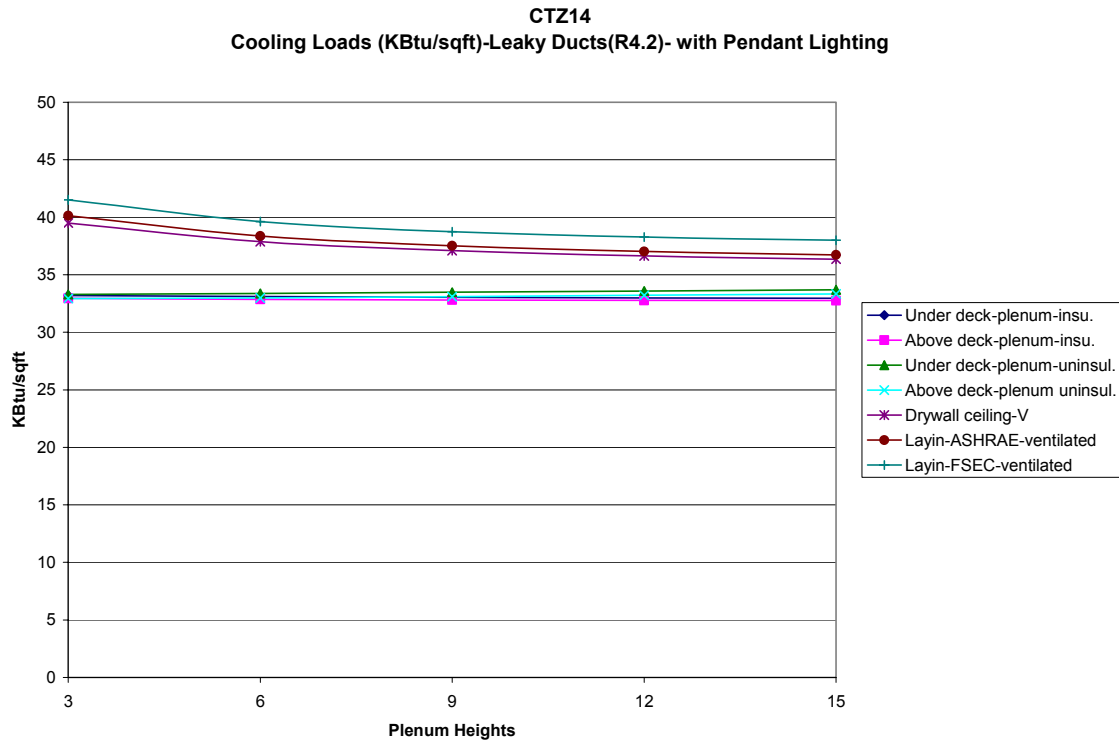
CTZ14						
Benefit cost ratio- insul. roof/drywall (tight ducts) vs insul. layin ceiling (tight duct)- FSEC						
	Insulated Plenum Wall		Uninsulated Plenum Wall			
Plenum Hts	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.	Drywall ceiling-UV	Drywall ceiling-V
3	5.09	2.19	9.20	2.74	1.09	1.54
6	2.77	1.45	7.15	2.14	0.92	1.37
9	1.86	1.10	6.17	1.86	0.90	1.30
12	1.39	0.89	5.58	1.68	0.91	1.26
15	1.10	0.75	5.19	1.57	0.94	1.24

Appendix B - Mass Wall with Pendant Lighting

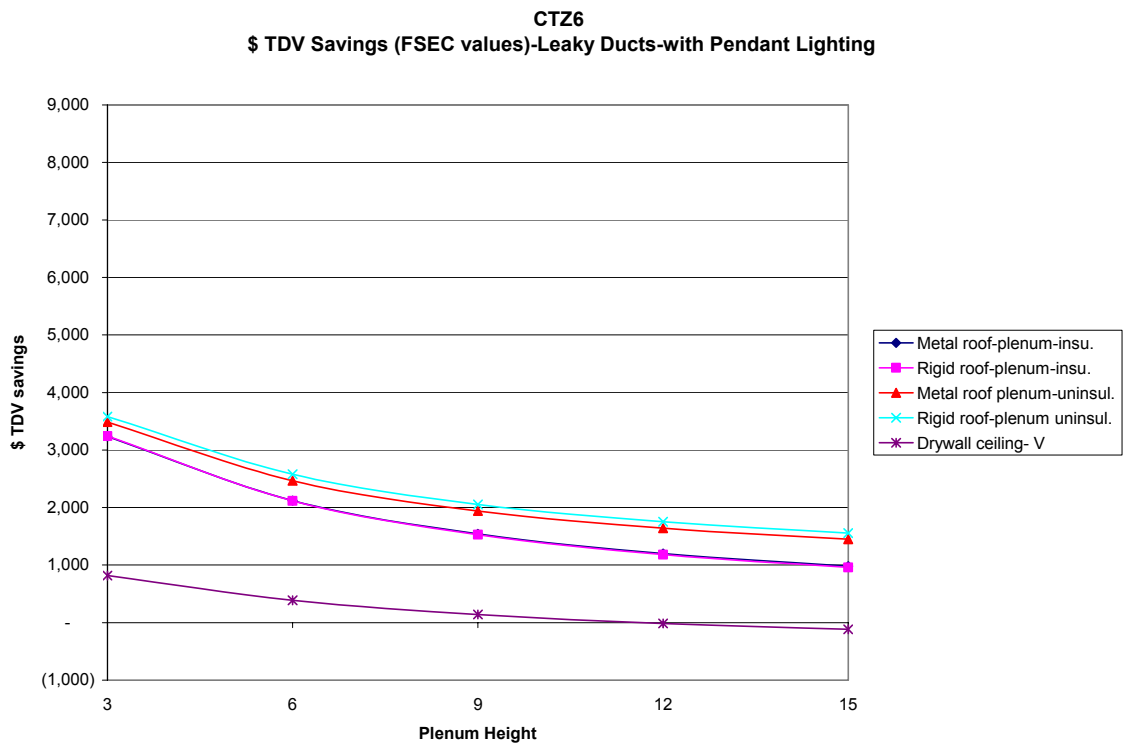
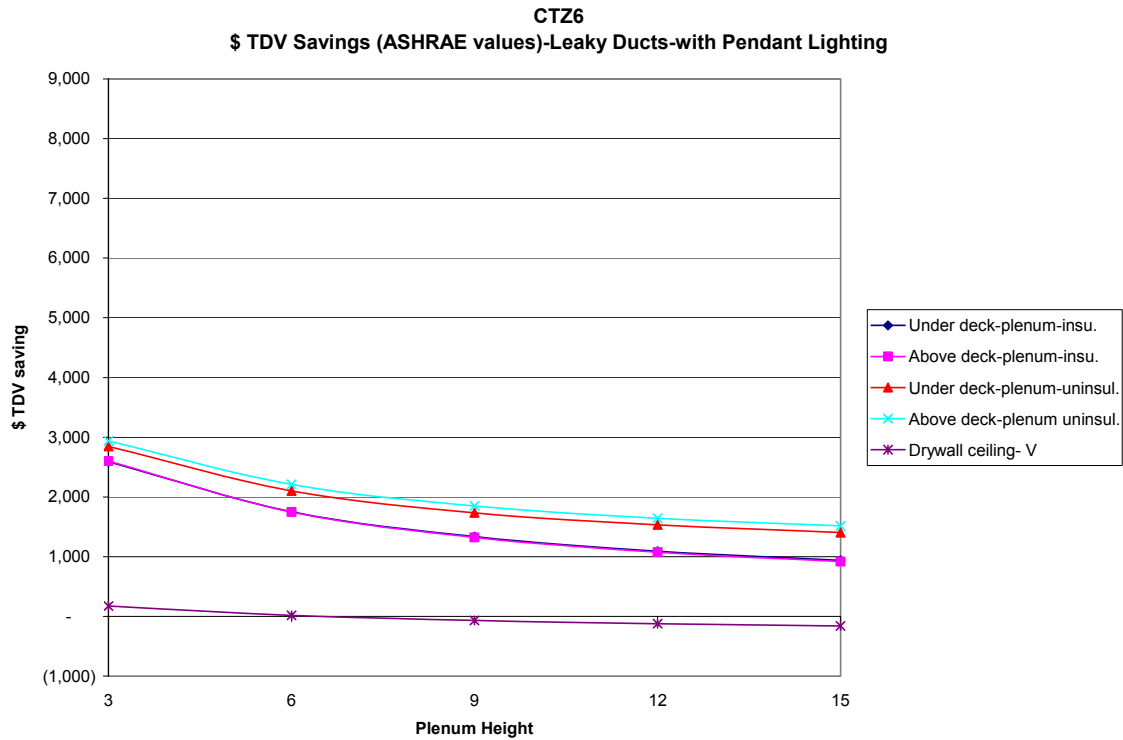
Energy Analysis

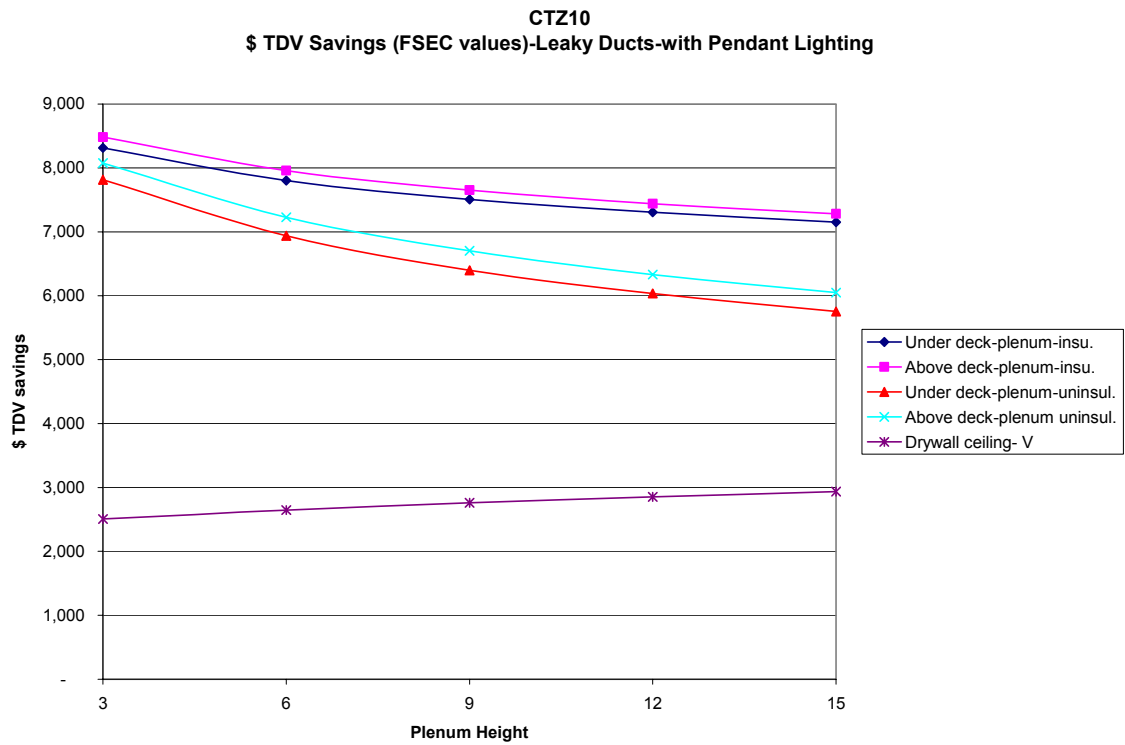
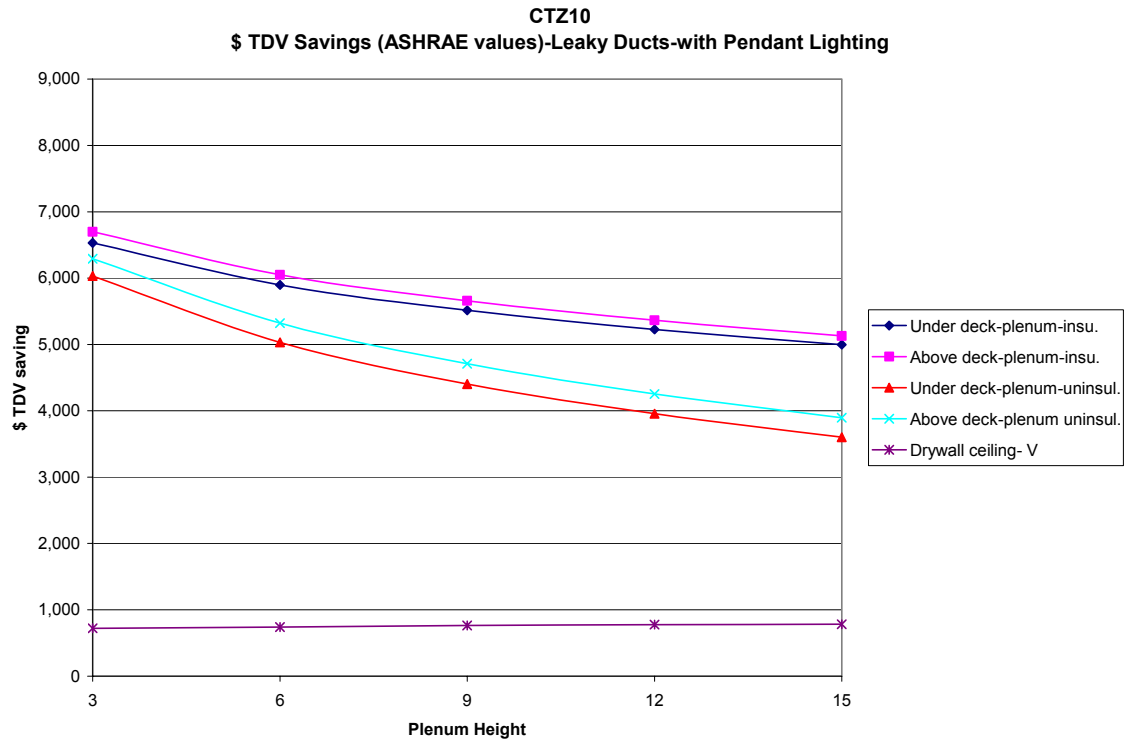


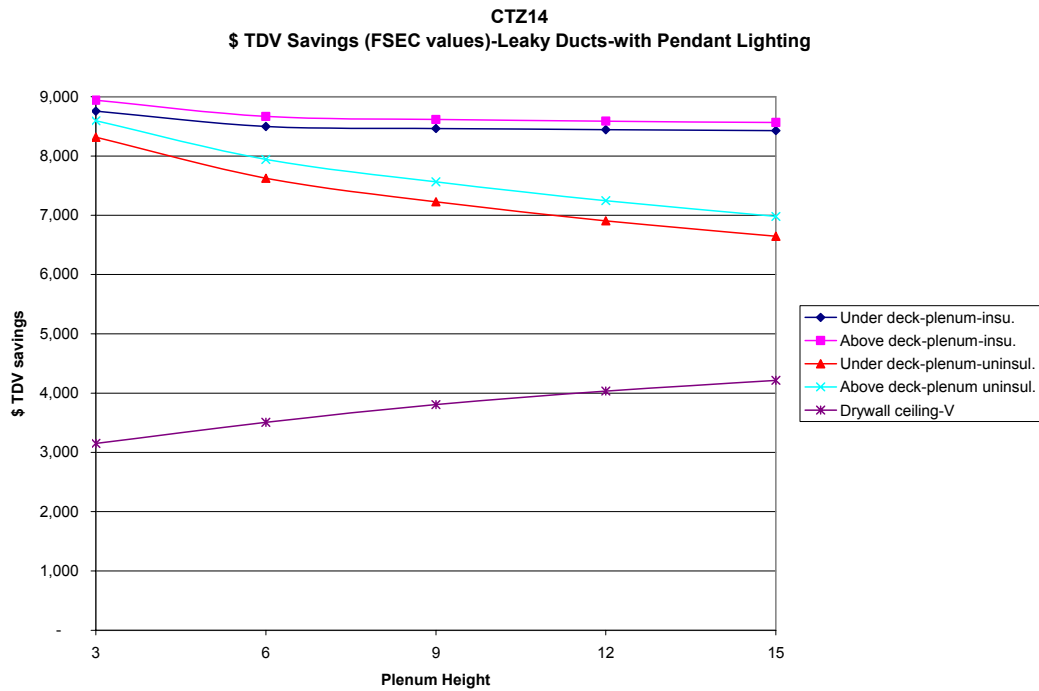
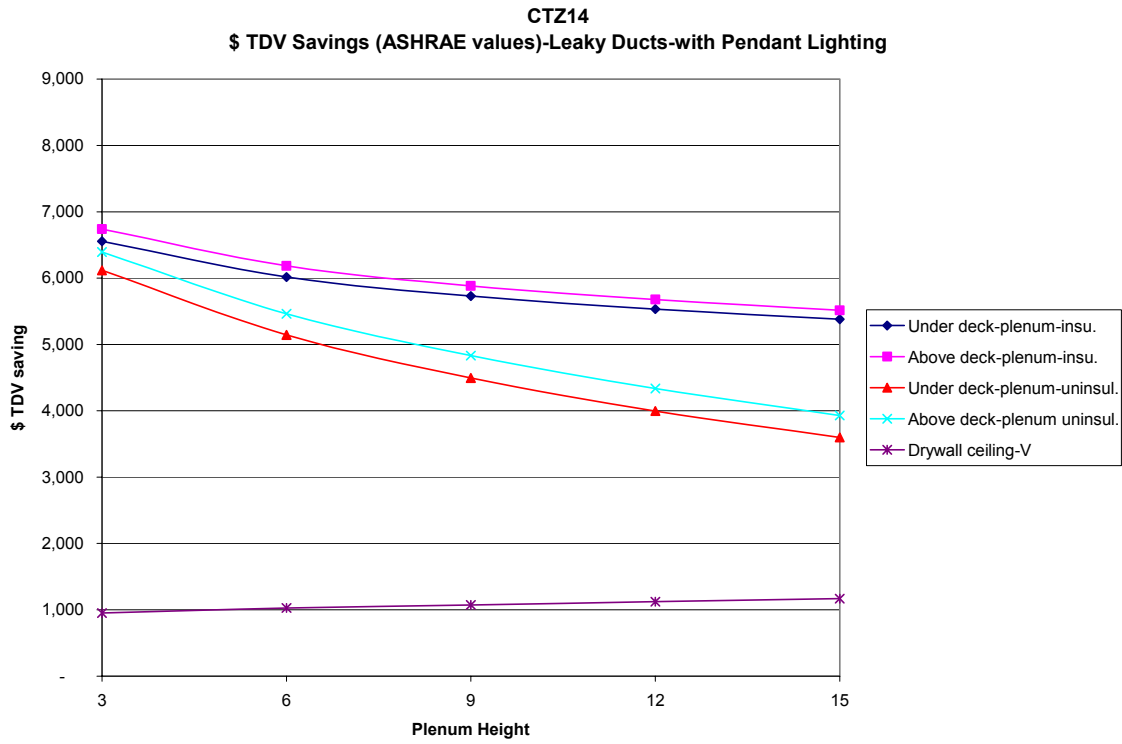




TDV Savings Analysis







Benefit Cost Ratio Analysis- Climate Zones 6, 10, 12, 14

Climate Zone 6

1. Benefit cost ratios of tightening and adding insulation to ducts for insulated roofs, drywall and lay-in ceilings from leaky (R 4.2) to tight (R 8)

Table 69: Benefit cost ratios of tightening and adding insulation to ducts for insulated roofs and drywall and lay-in ceilings from leaky (R 4.2) to tight (R 8) - Climate Zone 6

CTZ6 Benefit cost for tightening ducts for all insulation conditions							
	Insulated Plenum Wall		Uninsulated Plenum Wall				
Plenum Hts	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.	Drywall ceiling- V	Lay-in-V-ASHRAE	Lay-in-V-FSEC
3	0.94	0.89	1.25	1.14	4.90	4.66	4.05
6	1.17	1.12	1.65	1.52	4.65	4.63	4.41
9	1.36	1.33	1.94	1.81	4.46	4.52	4.50
12	1.53	1.51	2.14	2.02	4.34	4.44	4.54
15	1.69	1.67	2.30	2.18	4.26	4.38	4.56

2. Benefit cost ratios of insulated roof decks with leaky ducts (R 4.2) versus insulated lay-in ceilings with tight ducts (R 8)-Climate zone 3 for plenum heights of 3ft, 6ft, 9ft, 12ft and 15ft

Table 70: Benefit cost ratio of insulated roofs with leaky ducts (R4.2) versus insulated lay-in ceiling with tight ducts (R 8) using ASHRAE values -Climate zone 6

CTZ6 Benefit cost ratio-insul. Roofs (leaky ducts) vs insul. Ceiling (tight ducts) -ASHRAE				
	Insulated Plenum Wall		Uninsulated Plenum Wall	
Plenum Hts	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.
3	(0.52)	(0.23)	0.74	0.20
6	(1.20)	(0.74)	(23.49)	(0.99)
9	(1.08)	(0.76)	(33.70)	(1.50)
12	(0.93)	(0.60)	(38.84)	(1.77)
15	(0.80)	(0.64)	(41.88)	(1.93)

Table 71: Benefit cost ratio of insulated roofs with leaky ducts (R4.2) versus insulated lay-in ceiling with tight ducts (R 8) using FSEC values -Climate zone 6

CTZ6 Benefit cost ratio-insul. Roofs (leaky ducts) vs insul. Ceiling (tight ducts) -FSEC				
	Insulated Plenum Wall		Uninsulated Plenum Wall	
Plenum Hts	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.
3	1.75	0.79	35.47	1.95
6	(0.64)	(0.39)	(6.77)	(0.15)
9	(0.92)	(0.65)	(26.57)	(1.14)
12	(0.91)	(0.59)	(37.51)	(1.70)
15	(0.84)	(0.67)	(44.39)	(2.05)

3. Benefit Cost Ratio for Insulated roof decks and drywall ceiling with tight ducts (R 8) versus insulated lay-in ceiling with tight ducts (R 8)

Table 72: Benefit cost ratio of insulated roofs and drywall ceilings with tight ducts (R 8) versus insulated lay-in ceilings with tight ducts (R 8) with ASHRAE values for plenum heights of 3ft, 6ft, 9ft, 12ft and 15ft- Climate zone 6

CTZ6 Benefit cost ratio- insul. Roof/drywall (tight ducts) vs insul. Layin ceiling (tight duct)- ASHRAE					
	Insulated Plenum Wall		Uninsulated Plenum Wall		
Plenum Hts	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.	Drywall ceiling-V
3	0.32	0.20	1.23	0.68	0.10
6	(0.23)	(0.18)	0.49	0.29	0.01
9	(0.30)	(0.25)	0.29	0.19	(0.03)
12	(0.28)	(0.21)	0.25	0.17	(0.06)
15	(0.25)	(0.22)	0.26	0.17	(0.08)

Table 73: Benefit cost ratio of insulated roofs and drywall ceilings with tight ducts (R 8) versus insulated lay-in ceilings with tight ducts (R 8) with FSEC values for plenum heights of 3ft, 6ft, 9ft, 12ft and 15ft- Climate zone 6

CTZ6					
Benefit cost ratio- insul. Roof/drywall (tight ducts) vs insul. Layin ceiling (tight duct)- FSEC					
	Insulated Plenum Wall		Uninsulated Plenum Wall		
Plenum Hts	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.	Drywall ceiling-V
3	1.29	0.83	2.83	1.54	0.46
6	0.11	0.06	1.26	0.71	0.18
9	(0.19)	(0.16)	0.62	0.37	0.04
12	(0.27)	(0.20)	0.31	0.20	(0.05)
15	(0.27)	(0.24)	0.15	0.11	(0.10)

Climate Zone 10

1. Benefit cost ratios of tightening and adding insulation to ducts for insulated roofs, drywall and lay-in ceilings from leaky (R 4.2) to tight (R 8)

Table 74: Benefit cost ratios of tightening and adding insulation to ducts for insulated roofs and drywall and lay-in ceilings from leaky (R 4.2) to tight (R 8) - Climate Zone 10

CTZ10							
Benefit cost ratio for tightening ducts for all insulation conditions							
	Insulated Plenum Wall		Uninsulated Plenum Wall				
Plenum Hts	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.	Drywall ceiling- V	Lay-in-V ASHRAE	Lay-in-V- FSEC
3	0.99	0.90	1.55	1.35	8.62	7.90	6.38
6	1.22	1.14	2.27	2.01	8.94	8.72	7.90
9	1.43	1.35	2.85	2.56	9.03	9.10	8.73
12	1.66	1.58	3.34	3.05	9.11	9.33	9.28
15	1.89	1.81	3.78	3.48	9.17	9.49	9.68

2. Benefit cost ratios of insulated roof decks with leaky ducts (R 4.2) versus insulated lay-in ceilings with tight ducts (R 8)-Climate zone 3 for plenum heights of 3ft, 6ft, 9ft, 12ft and 15ft

Table 75: Benefit cost ratio of insulated roofs with leaky ducts (R4.2) versus insulated lay-in ceiling with tight ducts (R 8) using ASHRAE values -Climate zone 10

CTZ10 Benefit cost ratio for insul. Roofs (leaky ducts) vs insul. layin ceilings (tight ducts)-ASHRAE				
	Insulated Plenum Wall		Uninsulated Plenum Wall	
Plenum Hts	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.
3	3.87	1.00	Infinite *	1.03
6	0.71	0.34	20.36	0.05
9	0.04	0.07	96.02	(0.52)
12	(0.20)	(0.07)	147.88	(0.92)
15	(0.30)	(0.15)	188.16	(1.23)

Table 76: Benefit cost ratio of insulated roofs with leaky ducts (R4.2) versus insulated lay-in ceiling with tight ducts (R 8) using FSEC values -Climate zone 10

CTZ10 Benefit cost ratio for insul. Roofs (leaky ducts) vs insul. layin ceilings (tight ducts)-FSEC				
	Insulated Plenum Wall		Uninsulated Plenum Wall	
Plenum Hts	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.
3	9.91	2.41	Infinite *	2.89
6	3.34	1.34	Infinite *	1.68
9	1.65	0.85	Infinite *	0.99
12	0.94	0.57	Infinite *	0.51
15	0.58	0.39	6.73	0.15

3. Benefit Cost Ratio for Insulated roof decks and drywall ceiling with tight ducts (R 8) versus insulated lay-in ceiling with tight ducts (R 8)

Table 77: Benefit cost ratio of insulated roofs and drywall ceilings with tight ducts (R 8) versus insulated lay-in ceilings with tight ducts (R 8) using ASHRAE values for plenum heights of 3ft, 6ft, 9ft, 12ft and 15ft- Climate zone 10

CTZ10 Benefit cost ratio- insul roof/drywall(tight ducts) vs insul layin ceiling(tight Ducts)- ASHRAE					
	Insulated Plenum Wall		Uninsulated Plenum Wall		
Plenum Hts	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.	Drywall ceiling-V
3	2.21	0.97	3.65	1.12	0.38
6	0.92	0.50	1.93	0.62	0.30
9	0.47	0.30	1.11	0.38	0.25
12	0.27	0.19	0.64	0.25	0.23
15	0.16	0.13	0.33	0.15	0.21

Table 78: Benefit cost ratio of insulated roofs and drywall ceilings with tight ducts (R 8) versus insulated lay-in ceilings with tight ducts (R 8) using FSEC values for plenum heights of 3ft, 6ft, 9ft, 12ft and 15ft- Climate zone 10

CTZ10 Benefit cost ratio- insul roof/drywall(tight ducts) vs insul layin ceiling(tight Ducts)- FSEC					
	Insulated Plenum Wall		Uninsulated Plenum Wall		
Plenum Hts	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.	Drywall ceiling-V
3	4.78	2.05	8.20	2.43	1.32
6	2.49	1.30	5.94	1.78	1.13
9	1.58	0.94	4.81	1.45	1.02
12	1.12	0.72	4.15	1.26	0.96
15	0.86	0.59	3.72	1.13	0.92

Climate Zone 14

1. Benefit cost ratios of tightening and adding insulation to ducts for insulated roofs, drywall and lay-in ceilings from leaky (R 4.2) to tight (R 8)

Table 79: Benefit cost ratios of tightening and adding insulation to ducts for insulated roofs and drywall and lay-in ceilings from leaky (R 4.2) to tight (R 8) - Climate Zone 14

CTZ14 Benefit cost ratio for tightening ducts for all insulation conditions							
	Insulated Plenum Wall		Uninsulated Plenum Wall				
Plenum Hts	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum-uninsul.	Drywall ceiling- V	Lay-in-V-ASHRAE	Lay-in-V-FSEC
3	1.08	0.99	1.64	1.45	8.72	7.86	6.06
6	1.29	1.21	2.37	2.09	9.12	8.84	7.86
9	1.50	1.42	3.04	2.72	9.34	9.37	8.97
12	1.70	1.62	3.63	3.30	9.48	9.74	9.70
15	1.87	1.79	4.16	3.81	9.59	10.01	10.25

2. Benefit cost ratios of insulated roof decks with leaky ducts (R 4.2) versus insulated lay-in ceilings with tight ducts (R 8)-Climate zone 3 for plenum heights of 3ft, 6ft, 9ft, 12ft and 15ft

Table 80: Benefit cost ratio of insulated roofs with leaky ducts (R4.2) versus insulated lay-in ceiling with tight ducts (R 8) using ASHRAE values -Climate zone 14

CTZ14 Benefit cost ratio for insul. Roofs (leaky ducts) vs insul. layin ceilings (tight ducts)-ASHRAE				
	Insulated Plenum Wall		Uninsulated Plenum Wall	
Plenum Hts	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum-uninsul.
3	3.95	1.02	Infinite *	1.11
6	0.75	0.36	17.77	0.09
9	0.07	0.09	103.02	(0.55)
12	(0.16)	(0.05)	166.44	(1.03)
15	(0.26)	(0.12)	215.88	(1.42)

Table 81: Benefit cost ratio of insulated roofs with leaky ducts (R4.2) versus insulated lay-in ceiling with tight ducts (R 8) using FSEC values -Climate zone 14

CTZ14				
Benefit cost ratio for insul. Roofs (leaky ducts) vs insul. layin ceilings (tight ducts)-FSEC				
	Insulated Plenum Wall		Uninsulated Plenum Wall	
Plenum Hts	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.
3	11.31	2.75	Infinite *	3.37
6	4.13	1.65	Infinite *	2.19
9	2.23	1.13	Infinite *	1.48
12	1.43	0.83	Infinite *	0.96
15	0.99	0.64	Infinite *	0.56

3. Benefit Cost Ratio for Insulated roof decks and drywall ceiling with tight ducts (R 8) versus insulated lay-in ceiling with tight ducts (R 8)

Table 82: Benefit cost ratio of insulated roofs and drywall ceilings with tight ducts (R 8) versus insulated lay-in ceilings with tight ducts (R 8) using ASHRAE values for plenum heights of 3ft, 6ft, 9ft, 12ft and 15ft- Climate zone 14

CTZ14					
Benefit cost ratio- insul roof/drywall(tight ducts) vs insul layin ceiling(tight Ducts)- ASHRAE					
	Insulated Plenum Wall		Uninsulated Plenum Wall		
Plenum Hts	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.	Drywall ceiling-V
3	2.30	1.01	3.92	1.21	0.49
6	0.97	0.53	2.08	0.68	0.41
9	0.51	0.32	1.18	0.41	0.37
12	0.30	0.21	0.59	0.24	0.35
15	0.18	0.14	0.20	0.12	0.33

Table 83: Benefit cost ratio of insulated roofs and drywall ceilings with tight ducts (R 8) versus insulated lay-in ceilings with tight ducts (R 8) using FSEC values for plenum heights of 3ft, 6ft, 9ft, 12ft and 15ft- Climate zone 14

CTZ14 Benefit cost ratio- insul roof/drywall(tight ducts) vs insul layin ceiling(tight Ducts)- FSEC					
	Insulated Plenum Wall		Uninsulated Plenum Wall		
Plenum Hts	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.	Drywall ceiling-V
3	5.43	2.32	9.46	2.81	1.63
6	2.99	1.56	7.23	2.16	1.47
9	2.01	1.18	6.15	1.84	1.40
12	1.49	0.96	5.48	1.65	1.36
15	1.18	0.80	5.03	1.51	1.33

Appendix C: Detailed Cost Analysis

	Average of RS Means and survey	RS Means	Average from Surveys	No. of quotes
Suspended Acoustic Ceiling				
Mineral Fiber on 15/16" T bar suspension 2' x 2' x 3/4" lay-in board	2.76 \$/SF	3.46 \$/SF	2.06 \$/SF	3
2' x 4' x 5/8" tile	1.85 \$/SF	2.34 \$/SF	1.36 \$/SF	3
Fiberglass ceiling board, 2' x 4' x 3/4", plane faced	2.64 \$/SF	3.19 \$/SF	2.09 \$/SF	3
Offices, 2' x 4' x 5/8"	1.99 \$/SF	2.21 \$/SF	1.77 \$/SF	3
Lay-in Insulation				
Fiberglass, Kraft faced batts or blankets 6" tk, R-19 23"wide	0.57 \$/SF	0.69 \$/SF	0.46 \$/SF	4
Foil faced R-19	0.68 \$/SF	0.74 \$/SF	0.61 \$/SF	4
Fiberglass, Kraft faced batts or blankets 3-1/2" tk, R-11 23"wide	0.43 \$/SF	0.52 \$/SF	0.34 \$/SF	4
Foil faced R-11	0.55 \$/SF	0.60 \$/SF	0.50 \$/SF	4
Below Deck Insulation				
Panelized 2x6 w/ 24 oc and 8' bay - stapled to wood				
Fiberglass, Foil faced batts or blankets 6" tk, R-19 23"wide	0.72 \$/SF	0.74 \$/SF	0.70 \$/SF	3
Unfaced R-19	0.62 \$/SF	0.70 \$/SF	0.55 \$/SF	3
Metal Deck using imaping pins				
Fiberglass, Foil faced batts or blankets 6" tk, R19 23"wide	0.97 \$/SF		0.97 \$/SF	3
Unfaced R-19	0.82 \$/SF		0.82 \$/SF	3
Fiberglass, Foil faced batts or blankets 3-1/2" tk, R-11 23"wide	0.86 \$/SF		0.86 \$/SF	3
Unfaced R-11	0.71 \$/SF		0.71 \$/SF	3
Concrete Slab - Ins attached with glue pins				
Fiberglass, Foil faced batts or blankets 6" tk, R-19 23"wide	1.10 \$/SF		1.10 \$/SF	3
Unfaced R-19	0.92 \$/SF		0.92 \$/SF	3
Above Deck Insulation				
25 PSI comp strength, 4" tk, R-20	1.70 \$/SF	1.70 \$/SF	1.70 \$/SF	3
25 PSI, R-11	1.14 \$/SF	1.21 \$/SF	1.06 \$/SF	3
IB System 100 - 3600 SF Project	3.60 \$/SF		3.60 \$/SF	1
Above 3600 SF	2.75 \$/SF		2.75 \$/SF	1
Dry Wall Ceiling				
Framing only using hanging t-bars - Sheetrock screwed on	1.74 \$/SF	1.31 \$/SF	2.17 \$/SF	3
+ taping and finishing	3.27 \$/SF	3.13 \$/SF	3.42 \$/SF	5
Framing using studs spanning across walls. Max is 16ft. span	2.11 \$/SF		2.11 \$/SF	3
+ taping and finishing	3.10 \$/SF		3.10 \$/SF	4
Side Wall Insulation				
For tilt up walls - Using stick pins or Impaling pins				
Fiberglass, unfaced batts or blankets 3-1/2" tk, R-11 23"wide	0.58 \$/SF		0.58 \$/SF	3
Foil faced R-11	0.77 \$/SF		0.77 \$/SF	2
Unfaced R-13	0.66 \$/SF		0.66 \$/SF	2
Foil faced R-13	0.84 \$/SF		0.84 \$/SF	2
For framed walls - insulation pushed in place				
Fiberglass, unfaced batts or blankets 3-1/2" tk, R-11 23"wide	0.40 \$/SF	0.50 \$/SF	0.30 \$/SF	
Foil faced R-11	0.56 \$/SF	0.60 \$/SF	0.53 \$/SF	
Unfaced R-13	0.47 \$/SF	0.54 \$/SF	0.40 \$/SF	
Foil faced R-13	0.61 \$/SF	0.62 \$/SF	0.60 \$/SF	
Using furring, R-11 non rigid unfaced insulation	0.56 \$/SF	0.43 \$/SF	0.70 \$/SF	2
Using furring, R-13 non rigid unfaced insulation	0.60 \$/SF	0.43 \$/SF	0.78 \$/SF	2

*Percent value on right is the fraction of the cost that is labor

	Survey 1	Survey 2	Survey 3	Survey 4	Survey 5
Suspended Acoustic Ceiling					
Mineral Fiber on 15/16" T bar suspension 2' x 2' x 3/4" lay-in board 2' x 4' x 5/8" tile	1.43 \$/SF 35% 1.35 \$/SF 35%	3.00 \$/SF 40% 1.50 \$/SF 40%	1.75 \$/SF 40% 1.23 \$/SF 40%		
Fiberglass ceiling board, 2' x 4' x 3/4", plane faced Offices, 2' x 4' x 5/8"	1.65 \$/SF 35% 1.57 \$/SF 35%	3.25 \$/SF 40% 1.75 \$/SF 40%	1.38 \$/SF 40% 1.98 \$/SF 40%		
Lay-in Insulation					
Fiberglass, Kraft faced batts or blankets 6" tk, R-19 23"wide	0.47 \$/SF 30%	0.43 \$/SF 35%	0.48 \$/SF	0.45 \$/SF 15%	
Foil faced R-19	0.60 \$/SF 30%	0.67 \$/SF 35%	0.52 \$/SF	0.65 \$/SF 15%	
Fiberglass, Kraft faced batts or blankets 3-1/2" tk, R-11 23"wide	0.37 \$/SF 30%	0.31 \$/SF 35%	0.33 \$/SF	0.35 \$/SF 15%	
Foil faced R-11	0.50 \$/SF 30%	0.56 \$/SF 35%	0.39 \$/SF	0.55 \$/SF 15%	
Below Deck Insulation					
Panelized 2x6 w/ 24 oc and 8' bay - stapled to wood					
Fiberglass, Foil faced batts or blankets 6" tk, R-19 23"wide	0.69 \$/SF	0.72 \$/SF	0.70 \$/SF 20%		
Unfaced R-19	0.43 \$/SF	0.72 \$/SF	0.50 \$/SF 20%		
Metal Deck using impaling pins					
Fiberglass, Foil faced batts or blankets 6" tk, R19 23"wide	0.79 \$/SF	1.17 \$/SF	0.95 \$/SF 25%		
Unfaced R-19	0.53 \$/SF	1.17 \$/SF	0.75 \$/SF 25%		
Fiberglass, Foil faced batts or blankets 3-1/2" tk, R-11 23"wide	0.67 \$/SF	1.07 \$/SF	0.85 \$/SF 25%		
Unfaced R-11	0.42 \$/SF	1.07 \$/SF	0.65 \$/SF 25%		
Concrete Slab - Ins attached with glue pins					
Fiberglass, Foil faced batts or blankets 6" tk, R-19 23"wide	1.17 \$/SF	1.17 \$/SF	0.95 \$/SF 25%		
Unfaced R-19	0.84 \$/SF	1.17 \$/SF	0.75 \$/SF 25%		
Above Deck Insulation					
25 PSI comp strength, 4" tk, R-20	1.55 \$/SF 50%	1.50 \$/SF 30%	2.04 \$/SF		
25 PSI, R-11	1.20 \$/SF 50%	0.82 \$/SF 30%	1.17 \$/SF		
IB System 100 - 3600 SF Project				3.60 \$/SF 38%	
Above 3600 SF				2.75 \$/SF 38%	
Dry Wall Ceiling					
Framing only using hanging t-bars - Sheetrock screwed on + taping and finishing	4.50 \$/SF 5.70 \$/SF	4.50 \$/SF	1.15 \$/SF 2.45 \$/SF	0.87 \$/SF 1.94 \$/SF	2.5 \$/SF
Framing using studs spanning across walls. Max is 16ft. span + taping and finishing	3.50 \$/SF 4.70 \$/SF		1.96 \$/SF 3.26 \$/SF	0.87 \$/SF 1.94 \$/SF	2.5 \$/SF
Side Wall Insulation					
For tilt up walls - Using stick pins or Impaling pins					
Fiberglass, unfaced batts or blankets 3-1/2" tk, R-11 23"wide	0.50 \$/SF	0.65 \$/SF	0.60 \$/SF		
Foil faced R-11	0.65 \$/SF	0.80 \$/SF	0.85 \$/SF		
Unfaced R-13	0.61 \$/SF	0.68 \$/SF	0.70 \$/SF		
Foil faced R-13	0.75 \$/SF	0.83 \$/SF	0.95 \$/SF		
For framed walls - insulation pushed in place					
Fiberglass, unfaced batts or blankets 3-1/2" tk, R-11 23"wide			0.30 \$/SF		
Foil faced R-11	0.49 \$/SF	0.50 \$/SF	0.60 \$/SF		
Unfaced R-13			0.40 \$/SF		
Foil faced R-13	0.56 \$/SF	0.53 \$/SF	0.70 \$/SF		
Using furring, R-11 non rigid unfaced insulation		0.73 \$/SF	0.68 \$/SF		
Using furring, R-13 non rigid unfaced insulation		0.83 \$/SF	0.73 \$/SF		

*Percent value on right is the fraction of the cost that is labor

Appendix D: Onsite Survey Forms

Site ID:		Surveyor		Date	
Building Name:					
Building Address:				City	
Building Contact:				Phone	

Building age:	1968	No. stories	1
Last remodel:	1986	Total SF	1,163
Remodel description:	100% New construction		

Composition Tile	Flat	On top of roofing (rarely used)	Retail	
Other tile	Lo Pitch 2/12	Sandwiched (under roofing and above deck)	Office	
Built-up (tar)	Med 2-6/12	None	School	
Rubber membrane	Hi Pitch 6/12	Unsure	Manuf.	
Metal			Assembly	
Describe Other			(Other)	R.O.S.M.A & percent

Roof Code	Description	Sloped ?	Insulation above deck	Insulation thickness or R-factor	Approx Area (ft2)	Occ. under roof	2nd Occ. under roof
Rf1							
Rf2							
Rf3							
Rf4							
Total:							

Wood frame	Exterior	Loose fill	T-Bar (Y/N)	Y
Steel frame	Block core	Fiberglass batt	NOTES:	
Tilt up Cement	Between studs	Rigid		
Cement Block				

Wall Code	Construction Description	Insulation location	Insulation type	Insulation thickness or R-factor	Length (ft)
W1					
W2					
W3					
W4					

dimensions	clear	t-bar	Bldg type on plans cover sheet or code analysis
2' x 2'	white	sheetrock	Building type(I - V): ?
4' x 4'	bronze		
6' x 6'	prismatic	other, describe	vertical
4' x 8'	other, describe	none	splayed

Skylight Code	Size	Drop Ceiling (Y/N)	Quantity	Glazing color	Light well construction	Light well insulated	Well slope	Photo numbers or times
S1								
S2								
S3								
S4								